Science-1A Lab: Week-6, Wednesday, February 17, 2021

This is the lab where I do rapid-fire demonstrations of electromagnetism – how electric currents and magnetism interact. I will just try to describe each demonstration and hope that you can imagine what you would see if we were together in the lab.

I am grateful to the contributors to Google Images for the drawings shown below.

1. A moving magnet stirs electrons in a thick aluminum disk.

In the last few decades, the availability of extremely powerful permanent magnets has led to a revolution. The motor/generators in windmills, electric and hybrid cars, and various amazing toys depend on them. I used a very powerful 2.54-cm diameter, 2.54-cm long cylindrical magnet made of a rare-earth metal neodymium (Nd, element 60 on the Periodic Table of Elements). It was from *https://www.kjmagnetics.com/search-pn.asp?pg=1&stext=RX04X0* and cost about $20. The magnet comes with a warning sheet to caution against getting hurt during its use; it is dangerously powerful. Sometimes children are given smaller neodymium magnets that they swallow and end up with a serious, life-threatening situation where the magnets pull together in their gut and damage their small intestine.

Aluminum is not magnetic; a magnet does not pull at aluminum objects. But aluminum is a metal, and has electrons that can freely move within it. Those electrons do respond to a **changing** magnetic field so I pass around a 15-cm dia, 2.5-cm thick aluminum disk sanded on one side to a smooth finish. The big magnet is not attracted to the disk, but something strange is felt as the magnet is moved within a few mm of the surface of the disk. It feels like it is hesitant to approach the disk, but then gives up with no remaining opposition. Then, when lifting the magnet away from the aluminum disk, it again feels strange as if the disk doesn't want to let it leave. The effect is slight, but clearly noticeable.

I then ask the students to gently slide the magnet along the surface of the disk, and they feel a resistance to their sliding movement. It is as if they are stirring molasses. Something in the aluminum does not want the magnet to freely move. Upon stopping the sliding motion, no remaining force is felt – the force is only felt when the magnet is moving. The students were actually stirring electrons within the aluminum disk.

The electrons feel a force from the magnet's magnetic field, but only when that field is changing. What we have observed is that

A changing magnetic field causes a force on electrons.

It turns out that the electrons feel a force that is sideways to both the direction of the magnetic field and the direction of the motion. That force causes the huge swarm of about 10^{22} electrons to flow within that aluminum plate, and as they flow they bump into atoms and lose energy. It is that loss of energy that we feel as a resistance when moving the magnet. This type of electron flow is called an **Eddy current** and is a source of Eddy current heating in materials near a changing magnetic field.

2. A changing magnetic field within a coil of wire causes a voltage to appear across the coil ends.

This is actually the same phenomenon as mentioned above, but observed in a different way. A coil of wire is called a solenoid. One like that used in the lab is shown at the right. It has a hollow interior that we can slide magnets into while monitoring a voltage across the black terminals shown.

Voltages cause electric currents so we actually use a sensitive current device called a galvanometer with a moving needle that normally points straight up. If a current flows one way through the galvanometer its needle will move to the right, and if the current flows the other way its needle will move to the left.

We start the demonstration with nothing in the interior of the solenoid, and the needle points straight up. We then move a bar magnet into the solenoid from one end and the needle moves, perhaps to the right. If we lay the bar magnet down inside the solenoid, the needle returns to its vertical position.

Then, if we pick up the magnet again and continue moving it through the solenoid and out the opposite end, the needle moves in the opposite direction.

Turning the bar magnet around end-for-end reverses the direction of needle motion. We conclude:

A moving magnet inside a solenoid causes an electric current to flow in a direction that depends on the orientation of the magnet and whether the magnet is entering or leaving the coil interior.

It turns out that it does not matter whether the magnet is moving or the solenoid is moving. All motion is relative as famously pointed out by Einstein.

Since moving a magnet within a solenoid can cause an electric current to flow, we have an idea for an electric generator. Connect the magnet to a motor that keeps it moving in and out of the solenoid and we will have an electric flow back and forth through a wire that can light a light bulb. That is basically how an electric generator works.

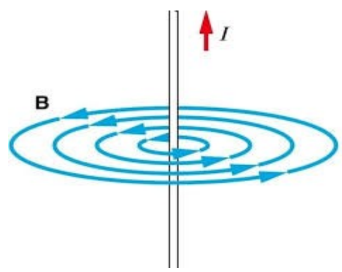
Alternatively, we can put a reversing electric current through a solenoid that can move a magnet and make a motor.

3. A magnet falling in an aluminum tube.
The note entitled "Magnet Falling Inside Aluminum Tube" at
https://yosemitefoothills.com/Science-1A/Handouts/Week-06/MagnetFallingInAlTube.pdf
explains a demonstration I do dropping a magnet into a 91-cm long, thick-walled aluminum tube with an inside diameter 1.27 mm larger than the magnet diameter.

While holding the tube vertical, I drop a plastic marking pen into the top end of the tube and it comes out the bottom 0.43 s later as can be calculated using $t=\sqrt{2h/g}$. But, when I drop the magnet used for demonstration 1 above into the top end, it slowly falls and comes out the bottom after 20 seconds. As explained in the note, the magnet causes electric currents to flow in the walls of the aluminum tube which then generate a magnetic field that tends to oppose the falling of the magnet. The magnet, by the way, is kept centered in the tube by those same magnetic repulsion forces.

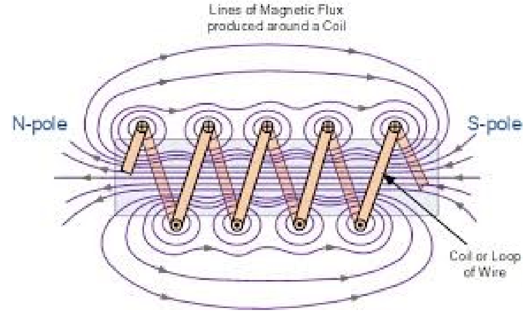
4. An electric current flowing through a wire produces a magnetic field around the wire.
For this demonstration, I use a power supply, a device that plugs into a wall outlet, but produces a voltage like that produced by a battery. A big advantage of a power supply is that the voltage is tunable from 0 V up to some maximum voltage. Power supplies also usually have meters that can show the voltage and how much current is being supplied.

I connect a long wire from the negative terminal of the power supply, and let it hang vertically with the lower end connected back to the positive terminal of the power supply. That produces the situation shown at the right. Current (denoted by the letter *I*) flows from the positive terminal upward to the negative terminal while electrons are flowing in the opposite direction. I ask a student to hold a small compass near different sides of the wire, and we note the direction of the compass needle. We are able to show that there is a magnetic field (denoted by the letter *B*) around the wire in the direction shown by the circular blue lines in the figure. We conclude:



A wire carrying current has magnetic field rings around it.

5. A solenoid can be used to enhance the magnetic field from the current flowing in a wire.
If we want a stronger magnetic field with the same current, we can wind a wire into a solenoid as shown at the right. Look carefully at how the circular magnetic fields from each turn blend together to strengthen the field in the solenoid center.



Small +'s and dots are used to show the direction of the current in the wire turns. This style of indicating current direction is to help the viewer imagine an feathered arrow going away from you, and you see only the feathered end. But if the arrow is coming toward you, you see the point represented as a dot. The tops of the turns in the drawing have current flowing away from the viewer while the bottom of those turns have current flowing toward the viewer. We conclude:

A solenoid is a device to produce a strong magnetic field from an electric current.

6. An increasing or decreasing magnetic field can push an aluminum ring.
This is actually the same effect as shown in item 1 listed above, but observed differently. When I moved into my wife's 60-year old ranch house 20 years ago, I noticed that its electrical wiring was without a ground connection. The outlets had only two connections, not the three required in modern houses. So I took out all the old 2-wire wiring and replaced it with 3-wire cables (more about house wiring next week). That left me with a hundred meters of old wire. Rather than get rid of it, I made it into two 250-turn solenoids with 10-cm cores wrapped around 10-cm long sections of large plastic water drain pipe mounted in a wood frame. I have used those ever since for class demonstrations of electromagnetism.

I first place one of those solenoids on the front desk so that its core is horizontal. Next, I hang a 2.5-cm thick aluminum ring with a 10-cm central hole in front of the solenoid's hollow core. I then use a car battery to energize the solenoid. The class can see the aluminum ring get slightly pushed away from the solenoid, and then settle back to its original position. Even though there is still current flowing through the solenoid producing a magnetic field, the ring no longer feels any force.

When I disconnect the car battery, the aluminum ring is briefly pulled closer to the solenoid and then settles back to its original position. More exciting is the nasty arcing spark visible at the place where the connection to the battery is broken. No comparable spark was noticeable when energizing the solenoid.

The explanation of the arcing is that the magnet had a large current flowing through its windings producing a strong magnetic field, and that magnetic field contained stored magnetic energy. When disconnected, that energy must go somewhere. As the field collapses hundreds of volts are generated in the coil by the collapsing magnetic field. That voltage causes electric current to jump across the disconnecting wires as they are pulled apart allowing the magnetic energy to leave the solenoid. The faster the connection is pulled apart, the greater will be the voltage. The magnetic energy must leave the coil as electrical current energy. All coils generate such a voltage, called a back voltage, when de-energized. It can cause trouble in circuits that are not able to handle it. That is why I use a car battery for that demonstration rather than a power supply.

Magnetic fields store energy that must go somewhere when the field is turned off.

The sparking is an exciting side-show, the main event was the pushing and pulling of the aluminum ring during the increasing and decreasing of the solenoid magnetic field. Just as we saw in demonstration 2 described above, a changing magnetic field will cause an electric voltage and current to flow in a solenoid. Here, the "solenoid" has a single turn – the aluminum ring. As the magnetic field increases inside of the aluminum ring, a current flows in the ring. Once the magnetic field has stabilized at a constant value, current no longer flows in the ring. This just like when the bar magnet was **resting** in the solenoid, and there is no deflection in the galvanometer.

But from demonstrations 1 and 4, current flowing in the aluminum ring will itself produce a magnetic field. It turns out that its magnetic field will oppose the solenoid field and therefore push the ring away from the solenoid. (It turns out that if nature did the opposite, we would have a way to get free new energy.) When the field of the solenoid collapses as its wires are disconnected, an opposite current will flow in the aluminum ring and it will be attracted to the remaining field in the solenoid, pulling the ring toward the solenoid.

An energized or de-energized solenoid can push or pull another solenoid (ring) because there will be an "induced" current and magnetic field in the second solenoid.

7. Magnetic domains enhance a magnetic field.
Next, a 20-kg steel cylinder is placed into the holes in the solenoid and hanging aluminum ring. When the solenoid is energized with this iron core, the effect is much greater. The ring jumps away from the solenoid and later slams back against the solenoid upon de-energization.

The iron cylinder has tiny regions, usually of micrometer dimensions called "magnetic domains" which have their magnetic iron atoms aligned together in the same direction. Normally, these many tiny magnetic domains are randomly oriented within the iron object and have no net effect. If, however, the iron object is placed in an external magnetic field such as that from a solenoid, its magnetic domains will become aligned and the iron will greatly enhance the field from the solenoid. That enhancement is what caused the greater effect in pushing and pulling the aluminum ring.

The magnetic domains in an iron magnetic core align and enhance the magnetic field of a solenoid.

When a magnet lifts a nail, the nail is temporarily magnetized so it is able to lift a second nail which can sometimes lift yet another nail. Once the first nail is removed from the original magnet, the remaining nails usually fall although some materials are able to remember their magnetism afterwards and be used as permanent magnets.

8. A segmented iron core improves efficiency.

The iron core itself ends up with induced currents flowing within it heating it up and wasting magnetic energy from the solenoid. This can be reduced by using many iron rods, each insulated from each other to reduce the amount of induced current flow in the iron core while still having the beneficial effect of the iron domains.

I have a second iron core made up of 48 hexagonal iron rods insulated from each other by plastic tape. Using this segmented core provides an even greater enhancement of the solenoid magnetic field and greatly reduced energy loss to heating.

Iron cores work better when segmented to minimize heating from induced current flow.

9. Magnetic levitation.

Next, I turn the solenoid and iron core into a vertical orientation. The aluminum ring is then paced over the free end of the core. Now, instead of the car battery, I connect the solenoid wires to a power cord and ask a student to plug it into an outlet behind the front desk. When the student plugs it in, the ring jumps up about 20 cm, usually falling off the end of the iron core. If re-positioned around the iron core, the ring levitates about 12 cm above the solenoid while the solenoid emits a humming noise. I then ask a student to press down on the ring to push it closer to the solenoid. The humming gets louder and the student must press with significant force. When held down for about 15 seconds, I ask if the student can report anything interesting and they report that the ring is getting warm. It turns out that although there is about 10 A of current flowing through the solenoid, it causes up to 2500 A of current to flow around the aluminum ring causing the warming.

The ring levitates because the magnetic field is constantly changing since the power from the outlet is "alternating" current (AC) in contrast to a battery's "direct" current (DC). The constantly changing current causes a constantly changing magnetic field which for reasons that are difficult to explain without AC circuit theory, causes a continual upward push against the ring. This is the principle of **magnetic levitation** which has been used to levitate railroad trains above their tracks to allow train speeds of over 350 km/h. The levitation reduces the rolling resistance of its wheels.

Magnetic levitation results from a metal reacting to a changing magnetic field or from a relative motion between a metal and magnetic field.

When the magnetic is moved across the disk in demonstration 1, faster motion caused a tendency for the magnet to be pushed away from the aluminum disk.

The military has produced weapons, called rail guns, that shoot projectiles accelerated by this same effect. The school has a small demonstration of these effects that shoots a small metal ring half-way across the room. If the ring is cooled with liquid nitrogen to 77 K, its electrical conductivity becomes about 8 times greater and it then shoots clear across the room.

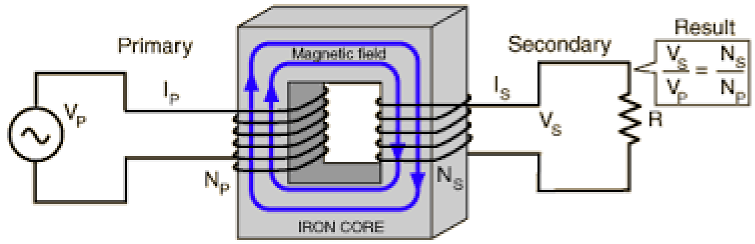
10. Electrical Transformers

Next, a second solenoid was placed around the iron core above the first solenoid and a light bulb was connected to the wires of the second solenoid. When the first coil was energized by being plugged into an outlet, the light bulb glowed even though there were no wires connecting it to any powered wires. The magnetic field from the first solenoid was causing enough voltage in the second solenoid to light the bulb. As the second solenoid was lifted away from the first solenoid, the light dimmed, showing that the coupling of energy was weakened. This kind of device is called an electrical transformer, it can be used to make voltages larger or smaller, but if it makes voltages larger, the available current is lower. If the voltage is made smaller, the available current can be larger.

This should make you think of the rules of a lever which trades force and distance. Here we trade voltage and current. The physics is the same, there is no gain in energy, just a different way to obtain it. Voltage multiplied by current is power, so if the voltage is doubled, the current must be halved so that the power remains the same.

An electrical transformer allows a trade off between voltage and current, but power is unchanged.

This is shown in the drawing at the right where instead of a cylindrical magnetic core, the core is made into a square loop, a more efficient design.



The ratio of voltages is proportional to the ratio of coil turns for the solenoids. If the second solenoid (called the **secondary**) has more turns, than the first solenoid (called the **primary**), then the secondary voltage will be greater.

This is reflected in equations at the end of the Chapter 6 section on page 3 of the Equation Sheet.

$$\frac{(\text{primary voltage})}{(\text{primary loops})} = \frac{(\text{secondary voltage})}{(\text{secondary loops})} \qquad \frac{V_p}{N_p} = \frac{V_s}{N_s} \quad \text{or} \quad \frac{N_s}{N_p} = \frac{V_s}{V_p} \quad \text{and} \quad P_p = P_s \quad \text{or} \quad I_p V_p = I_s V_s$$

11. Tesla Coil

A Tesla coil is a very clever device invented by Nicolas Tesla. It is actually of no practical value except as a great demonstration of physics. It is described at *https://yosemitefoothills.com/Science-1A/Handouts/Week-06/TeslaCoil.png* .

The handout shows its circuit diagram, and gives an explanation of how it works that is actually aimed at more advanced physics classes. Basically, it is two transformers, one taking the voltage from the 120 V wall outlet voltage to 17 kV with a resonant circuit at 60 Hz, and a second transformer taking the voltage up to 200 kV with a resonant circuit at 595 kHz. The spark gap provides a kick to the high-frequency circuit 120 times per second which keep its voltage active.

I start by holding wire connected to the Tesla coil base and bring its tip close to an 8-cm diameter globe at the top of the second coil. 5 cm long sparks then jump to the end of the wire that I am holding by its insulated covering.

I next bring a fluorescent light tube within about 30 cm of the top globe and it lights up all the way to the place where I am holding it near the other end. I feel nothing at that time, but clearly the electricity is leaving the fluorescent bulb and going to the floor through my body. The bulb is lit from the strong electric field in the space around the top of the Tesla coil.

I next lower the end of the bulb with its metal contacts close to the globe and sparks jump to those contacts. I then feel something, but I know that the high frequency 594 kHz voltage flows over my skin ("skin effect") and does not get near my heart.

I don't let the students use the Tesla coil because touching the 5.5-turn coil can easily kill someone since its 17 kV is at the dangerous frequency of 60 Hz and it can provide a very large, deadly current.

There are many "Tesla Coil" YouTube videos, but I did not see any I thought I should link here.

To earn credit for this lab, report that you have done the following:

1. Report that you read this note and imagined the demonstrations that are described here. (Too bad I have been unable to show them to you.)
2. Read the handout about the falling magnet in an aluminum tube.
3. Looked at the Tesla Coil handout.