Basic Electricity and Magnetism

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Lesson Focus

This lesson forms part of a trio of inter-related lessons, the other two being "Basic Electric Transformers" and "Basic Electric Generators and Motors". Since these lessons are intended for the younger students, the tone of the writing is deliberately light hearted.

The existence of electricity has been known to mankind almost from the beginning of time, notably in the form of lightning. Two of the early experimenters in this field were Ben Franklin (1706 – 1790) and Luigi Galvani of Italy (1737 – 1798). Franklin, is of course, generally known for his experiment of flying a kite into a thunder cloud and obtaining a spark from a key attached to the end of the kite string. (Franklin was not as foolish as might seem: see below). Galvani is best known for his accidental discovery that when he was dissecting a frog's leg, it twitched when touched with a scalpel which had become electrically charged after being wiped on a clean dry cloth. (Note the trick of rubbing a plastic pen on your sleeve and then picking up a very small chip of paper). Galvani published his findings in 1780.

Magnets have also been known to mankind for many centuries, in the form of compasses used by seafarers. But the needles in these compasses were generally formed from naturally occurring materials, or by stroking a piece of iron with another piece which was already magnetized. It was only within the last 200 years or so that it was discovered that magnets could also be made by passing an electric current through a coil of wire and placing pieces of iron inside the coil.

Capacitance, on the other hand is a comparatively recent discovery, dating from the early 1800's, and represents a means of storing very small amounts of electrical energy for very short periods of time, even after the applied voltage has been removed. As such it should not be confused with the storage batteries used to start cars and keep laptops going when the power is off. For more on this, see the section on capacitors below.

Lesson Synopsis

The lesson begins by outlining the work of some of the early experimenters and the sequence which eventually led to the realization of how a changeable electro-magnetic field could be harnessed to other purposes. From there the lesson goes on to demonstrate how electric currents, magnetic fields and electro-static fields are so closely related. A series of simple hands-on activities are provided at the end of the lesson.

The lesson ends with a section in which the students are invited to discuss with the teacher, various ways in which they think these demonstrations could be improved.

Age Levels

It is suggested that the first section below, that dealing with Ohm's Law, is suitable for students in Primary School. The remainder of the lesson could be more suitable for students in High School.

Objectives

Students will:

- Gain a useful initial acquaintance with the most common elements of electricity and electrical equipment.
- Learn about how magnets are made and what they do.
- Learn about circuits, switches, conductors, resistors and batteries etc.
- Learn about what capacitors are made of and what they do.
- Learn the meaning of insulation and why it is necessary.
- Learn some basic safety precautions.
- Learn about the importance of discipline and team work.

Anticipated Learner Outcomes

As a result of this activity, students should develop an understanding of:

- Electricity and magnetism
- Engineering history
- problem solving
- teamwork

Lesson Activities

- It is suggested that the students assist the teacher in obtaining the simple materials – mostly short lengths of soft iron or steel bar. One similar length of a non-magnetic material such as brass or aluminum would also be useful. A small quantity of iron filings (say a teaspoon full) would also be required. The students will be able to help the teacher to make these filings if necessary.
- A simple experiment, using three LEDs, a capacitor and a 6 Volt lantern battery is also outlined at the end of this lesson.

Resources/Materials

- Teacher Resource Documents (attached).
- Student Resource Sheets (attached)

Alignment to Curriculum Frameworks

- See attached curriculum alignment sheet.

Internet Connections

- TryEngineering (www.tryengineering.org)
- ITEA Standards for Technological Literacy: Content for the Study of Technology (www.iteaconnect.org/TAA)
- NSTA National Science Education Standards (www.nsta.org/publications/nses.aspx)

Recommended Reading

- Wikipedia "How Magnets are Made".
- Wikipedia "Capacitor"
- Google "Van de Graaff Generator".
- IEEE magazine "Spectrum", "The Long Road to Maxwell's Equations", James C. Rautio, December 2014.
- Faraday, Maxwell and the Electromagnetic Field, Forbes and Mahon, Prometheus Books, 2014, ISBN 978-1-61614-942-0.

Optional Writing Activity

- Having discussed the obvious limitations of this very simple demonstration unit, students should be asked to set out ways in which they think it could be improved.

For Teachers:
Teacher Resources

Materials and Costs
To all intents and purposes, the material costs for this demonstration are virtually zero. Iron filings may be purchased at online stores which sell science supplies.

Safety Note.
Magnets and flashlight batteries are, of course perfectly harmless. However teachers should be made aware of the fact that a Van de Graaff electrostatic generator and machines of that type, as described below, can easily produce very considerable voltages ranging into the thousands of volts. They are therefore not suitable for classroom demonstration. Teachers and students should be content to read of the theory and application as described in this lesson and the reference material appended.

◆ **Time Needed**

It is suggested that, for the younger students, aged between **8 and 10,** the lesson should be confined to the sections on magnetism and electric circuits. For this, three sessions of 45 minutes each should be sufficient.

For the older students, aged between **11 and 15**, the balance of the lesson, covering capacitance (the ability of a body to store an electrical charge), insulation and safety, could be covered in three or four more sessions of 45 minutes each. The format of the text is such that much of the material could be assigned as homework.

GETTING STARTED

Basic Electricity

As mentioned in the introduction above, one of the earliest known experimenters in electricity was the American, Benjamin Franklin (1706-1790) who in 1752 flew a kite into a thunder cloud with a key attached to the end of the string. From what we know today, Franklin was nowhere near as foolish as it might seem. He knew what he was doing. He stood on a large wooden box (an insulator) and attached the end of the string to an iron rod driven deep into the ground. Today this would be known as "grounding", which is an integral part of all Electrical Safety Codes. Franklin, of course, was an inspired amateur rather than a scientist, and went on to a famous career in politics, being a signer of the American Declaration of Independence in 1776, and the Constitution in 1787.

The first scientific inkling of what electricity might be, is attributed to the Italian, Luigi Galvani (1737-1798). While he was dissecting a frog's leg, he wiped the scalpel with a dry cloth, thereby putting a slight electrostatic charge on the scalpel. When the scalpel then touched the leg, it discharged and the leg twitched vigorously.

Galvani published his observation in 1780, but for some years after, the cause was not understood, and of course there was no means of measuring electricity in those days. At first it was believed that the twitch came from some mysterious energy within the leg. In memory of Galvani, the terms "Galvanic Action", "Galvanized coating", and being suddenly "Galvanized into action", came into use.

However, in 1800, another Italian researcher, Alessandro Volta (1745-1827), who had been trying to solve Galvani's puzzle, discovered that if he assembled a small pile of metal discs, alternatively of copper and zinc, separated by discs of blotting paper soaked in salt water, he could produce a reasonably steady and readily available source of electricity. See Figure 1.

Fig. 1: The Original Voltaic Pile
Source: Wikipedia

Of course, at that time he had no means of measuring the strength of the voltage. Still less could he understand what electricity really was or how it could be measured. Volta published his findings in 1820, and the electrical term **VOLT** has been adopted in his memory. **It should be understood that Volta's discovery of the "Voltaic Pile" was one of tremendous importance, because it meant that for the first time, a (reasonably) reliable and steady source of electricity could be made available on demand. Unfortunately, Volta does not seem to have been accorded anywhere near as much fame as he deserves.**

The year 1820 was one of amazing activity. Firstly, a German researcher, Johann Schweigger (1779-1857) managed to develop a simple measuring instrument. This comprised a very small, light, mirror suspended vertically from above and below on a silk thread, and the whole being enclosed in a glass jar. The jar was simply for protection and was not vacuum-tight. In Figure 2, the interesting thing here is that this instrument was not named after its' inventor, but after Luigi Galvani (above).
Thus Galvani is one of a very few scientists
who have had their names attached to a discovery which he did not personally make.

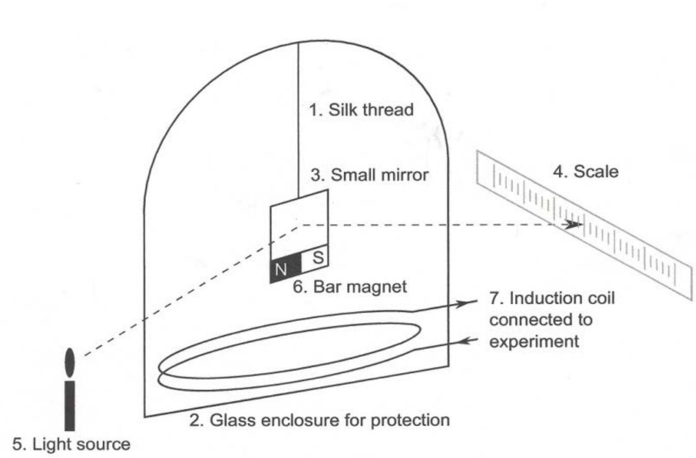


Fig. 2

Again, in 1820, and almost coincident with the discovery of the Galvanometer, the Danish scientist, Hans Christian Oerstead (1777-1851) discovered the phenomenon of electromagnetism. He just happened to have a small magnetic compass lying close to a short length of copper wire. Oerstead noticed that whenever the wire was carrying any current, the needle of the compass would deflect off to one side. The stronger the current the greater the deflection. When the current was switched off, the needle would return to normal, and if the current was reversed, the compass would deflect to the opposite side. See Figure 3.

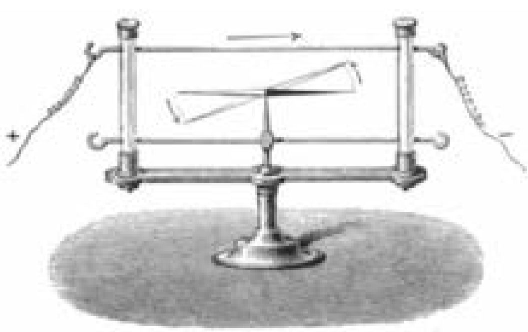


Fig. 3
Source: Wikipedia

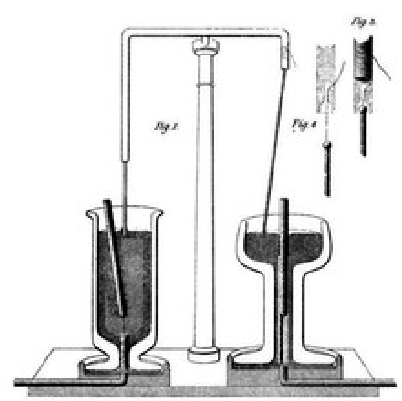


Fig. 4
Source: Wikipedia

In the next year (1821) the English scientist, Michael Faraday (1791-1867) read of Oersteads' discovery. Firstly, he repeated Oerstead's experiment to satisfy himself that the compass needle really did deflect. Then, in a stroke of genius typical of Faraday, he conducted several more ambitious experiments to see if he could get the compass needle to rotate through a full 360 degrees. Eventually he was more successful than he anticipated. He placed a bar magnet upright in a pool of mercury, and suspended a light copper wire in such a way that the tip of the wire just touched the mercury. See Figure 4.

The glass jar on the left is his "Voltaic Pile". The wire in a pool of mercury is on the right. To his amazement and to his own satisfaction, the wire not only rotated, but continued to do so at quite a high rate of speed. In effect, Faraday had discovered the basis of the electric motor, although the practicality of developing this into an industrial concept was beyond the technology of the day, (1821). **Safety Note**. While most of the early experiments described in this lesson can be reasonably repeated in a modern classroom, the above experiment should **NOT** be attempted because mercury is highly toxic.

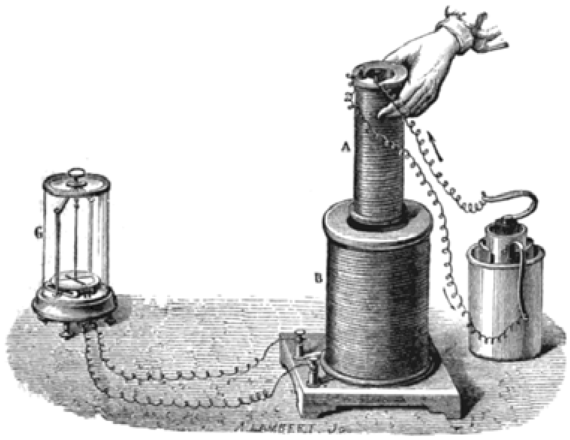


Fig. 5
Source: Wikipedia

Over the next 20 years or so, Faraday carried out literally thousands of experiments aiming to discover just what electricity and magnetism really were. One of his better known experiments is illustrated in Figure 5. This experiment dates from about 1831 and demonstrates his discovery that any change in the linkages between the lines of magnetic force (See **Basic Magnetism** below) and the turns of wire in his coil, would produce a small voltage which deflected the Galvanometer. While the movable coil was stationary there was no deflection, but when the coil was withdrawn, the deflection was in the opposite direction. In effect, and presumably without knowing it, he had discovered the basis of an electrical generator and a transformer. (See related Lesson Plans – "Basic Electric Generators and Motors", and "Basic Electric Transformers".

For the next 30 years or so, Faraday continued his meticulous experiments. In particular, he was puzzled by the fact that magnetism and light could pass through a vacuum, but electricity could not. Also by the discovery of others that electricity and light seemed to travel at about the same speed (300,000 km per second). But that's a story for another day.

However, if there was a limitation in Faraday's work, it was that his results were often difficult to quantify and predictive calculations were difficult and in fact probably not possible. This was not Faraday's fault; it was simply that the necessary mathematical techniques, such as vector analysis etc. had not them been developed. It was not until some 30 years later that a young Scottish mathematician called **James Clerk Maxwell** (1831-1879) managed to develop the algebra required to calculate (and to prove correct!) the experimental work which Faraday had done. But even Maxwell's equations were highly complex and difficult to understand. (There were 24 equations and he required 3 volumes to explain them). So about another 20 years later again another scientist **Oliver Heaviside** (1850-1925) managed to boil them down to four "simple" equations, which only required two volumes to explain! But that's another story for later. It is interesting to note that Faraday lived long enough to meet Maxwell, although his view on the 24 equations were not recorded.

At this point the story of electricity and magnetism become intertwined. So let's look at the next section.

BASIC MAGNETISM

The only common metal which can be easily magnetized is that which contains a large proportion of iron. Hence this is known as a "ferrous" metal, from the Latin word ferrum, meaning iron. Most other common metals, such as copper, aluminum and chromium etc., cannot be magnetized to more than a very small extent, and as soon as the magnetizing force is removed, they relapse back into their original non-magnetic state. Ferrous metals, on the other hand, will not only make quite strong magnets, but many (but NOT all) of them will retain their magnetism for long periods, many years in fact. In contrast, however, ferrous metals are generally not very good electrical conductors (relatively high resistance). Furthermore they tend to oxidize (rust) quickly, whereas the non-ferrous metals mentioned above are generally very good conductors of electricity (very low resistance) and do not oxidize very much.

North and South Poles.

Obtain two bar magnets. These are generally found in pairs, and are about 6" (15 cm) long. If you don't already have them, simply locate almost any piece of iron or steel rod and cut off two pieces, each about 6" (15 cm) long. Precision is not necessary. Even two lengths of threaded rod available in any hardware will do. Take these to your nearest automobile electric repair shop and ask them to magnetize them for you. Tell them it is a school project and they will probably do it for nothing. The magnets should be strong enough to pick up a large (steel) washer.

Note: For good measure try and locate a piece of brass, copper or aluminum. These metals are non-magnetic and will serve as an example of what is and what is not a magnetic material.

A small quantity of iron filings will also be required. A teaspoon-full will be plenty. You can also make these yourself by filing down an old piece of scrap iron.

Magnetic Polarity

Take one of your bar magnets and suspend it from a piece of string in such a way that it is suspended horizontally and free to swing in a circular manner. Hang this from a hook in a doorway or similar. After a few minutes you should be able to notice that the magnet slowly swings until it is more or less in a North-South position. Mark the end pointing North with a piece of adhesive tape. Repeat the exercise with the other magnet, and also mark the end pointing North. Strictly speaking, these two ends are known as the "North **Seeking**" poles. However the word "seeking" is usually dropped, and they are simply called **North** poles. Similarly the other ends are known as the **South** poles.

Magnetic Attraction
If you take both bar-magnets and gradually bring a north pole close to a south pole, you will find that the two will come together with a satisfying click. And then they will be relatively difficult to pull apart. Conversely, if you try to bring two north poles together (or bring two south poles together), they will kick away from each other, no matter how much you try. This illustrates the convention that "**unlike poles attract**", and "**like poles repel**".

If you have made yourself a length of non-magnetic material, you will find that when hung from a piece of string, it will not try to point in any particular direction. Similarly, neither of your bar magnets will be able to pick it up.

Lines of a Magnetic "Field" (or Magnetic Flux)
Unfortunately magnetism cannot be seen, although it can certainly be measured. Figure 6 illustrates the general concept of what are known as "lines of magnetic force". Lay one of your bar magnets flat on the table and cover it with a sheet of newspaper. Sprinkle some of your iron filings on the paper. You will find that they form a pattern like that in Figure 6, with the filings bunched together at the ends, and curving away towards the other end, where they bunch up again.

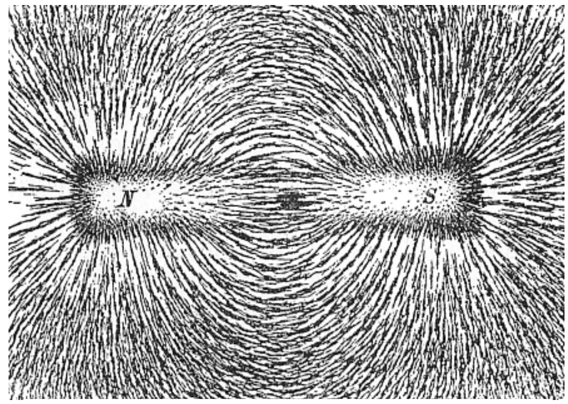


Fig. 6

Note 1: Try to avoid letting the iron filings come into contact with the magnets, because they will be very difficult to remove!

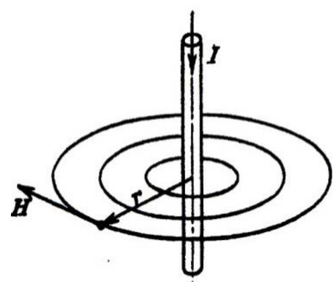
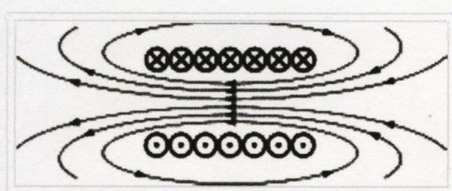


Fig. 7

Note 2: Modern permanent magnets can be surprisingly strong. For example, a magnet 1" (2.5 cm) in diameter can support 30 pounds (13 kg). Such magnets can be bought in almost any toy store in packets of 5 for $25.00, or $5.00 each.

Flux Density
A related concept is that of "Flux Density". In other words, the more closely the lines are bunched together (notably close to the two ends of the magnet), represents a higher flux density. These densities can actually be measured and calculated, but require sensitive instruments, and we will skip that here. For many years the unit of flux density was measured in "lines per square cm", and the unit was known as a Gauss, after the early German experimenter, Carl Friedrich Gauss, 1777 - 1855. However in 1960 the international unit of flux density was changed to the **Tesla, or T,** named after the famous pioneer, Nicola Tesla (1856 – 1943). A unit of one T = 10,000 Gauss.



Magnetic field lines of a solenoid which are similar to a bar magnet as illustrated above with the iron filings

Fig. 8

Electromagnets

It was during these experiments by Gauss, Oerstead, Faraday et al, that it was discovered that the passage of an electric current through a wire (probably copper or soft iron in those days.) produced a small magnetic field around itself.
See Figures 3 and 7.

It was further discovered that this magnetic field could be intensified if the wire was wound up into a cylindrical coil. (See Figure 8 and note the similarity to the flux around a bar magnet shown in Figure 6). This was a useful discovery for certain applications, because as we have seen above, as soon as the electric current is cut off, the magnetism around the coil collapses again to zero.

A Note for Older Students

As a matter of interest, many military and research ships have what is known as a "de-gaussing cable" looped around the full perimeter of the upper deck. A DC current is circulated through this cable, and adjusted so that the magnetic field produced by the current is equal to and of opposite polarity to the natural magnetism of the ship's hull. The effect of this is to render the ship more or less non-magnetic and therefore (in the case of a military ship) "invisible" to magnetic mines lying beneath the surface, and in the case of a research ship, would not interfere with the sensitive instruments on the vessel.

Magnetic Permeability, Saturation and Hysteresis

Magnetic Permeability: By this point the concept that ferrous metals make good magnets should be relatively clear. By experiment over the years, metallurgists have found that different grades of iron make different (i.e. stronger or weaker) magnets. Similarly that some grades of iron can retain their magnetism over very long periods (years), while other will lose it almost as soon as the electromagnetic current is cut off. This can be measured and is calculated in terms of the number of (magnetic) lines per square cm of cross section of the iron used. By way of illustration, a common figure for a maximum flux density in ordinary soft iron or mild steel is about 15.000 lines per square cm. In other words the iron mentioned above would be said to have a permeability of 15,000. By contrast, and as a standard reference, the permeability of air is taken as 1.00. This is a very important concept to keep in mind, because it tells us that if you have a magnet which has only a coil of wire with air inside, you will need 15,000 times more effort to produce a magnet of the same strength. This is a huge difference. Or conversely, with a coil of wire having an iron core inside it, you can get the same strength using 1/15.000 (0.000066) the amount of effort! The student should appreciate, however, that the matter of "lines of magnetic force per square cm" (or square inch) is purely a concept to facilitate calculation. They cannot be seen or measured with the naked eye.

Saturation: Following on from the above, most steels exhibit a marked tendency resist additional flux density beyond a certain point. In other words, the steel simply does what the word implies – it saturates, and cannot be further magnetized.

Magnetic Hysteresis:

During their early investigations, the pioneers in this field made another interesting discovery. They plotted a graph of the flux density (lines/sq. cm) versus current in the coil. This current, was of course DC from a battery. See Figure 9 and examine it in the following sequence:-

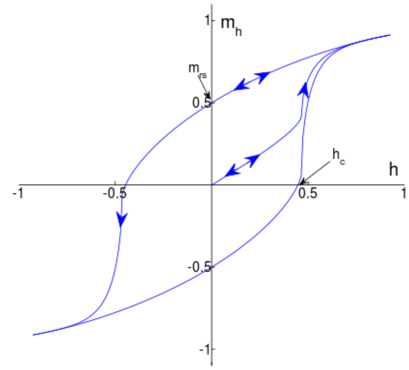


Fig. 9

1. The vertical axis represents the flux density in the magnetic material. This is measured in **lines per square cm** of the material or lines per square inch as the case may be. The international symbol for magnetic flux is **B**. The horizontal axis represents the force which is producing the magnetization, in this case a coil of wire surrounding the steel. The international symbol for magnetizing force is **H** and is measured in **Oersteads** after the early Danish experimenter Hans Christian Oerstead. In practical terms however, what you would be measuring would be the current (amps) in the coil of wire. You would of course, switch on the current and gradually increase it, taking measurements as you go.
2. Examine now the central point of the diagram where the two axes intersect. The first time you attempt to magnetize a new core, you would obtain a curve similar to the dotted line here.
3. Eventually you would find that even though you keep increasing the magnetizing current, you would not get any more lines of flux. This point is known as the **Saturation Point**. (Point **a** on the graph). Then, as you gradually decrease the current in the coil, the flux density would reduce also, but not as quickly as it increased on the way up.
4. Eventually, at the point where you are applying no magnetizing force at all, you will find that you still have a small amount of magnetism remaining in the steel. This would be point **b** on the curve. This point is known as the **retentivity** or **remanance**.
5. Next you would reverse the connection of the battery and begin gradually increasing the current in the opposite direction. At point **c** on the curve you would reach zero magnetism. This point is known as the **coercivity** point, because you have been trying to "coerce' the magnet back to zero.
6. From then on, as you gradually increase the magnetizing force, you will reach a saturation point but of the **opposite polarity**. This is represented by point **d** on the curve.
7. From then, it is all downhill, so to speak, because you will find that as you decrease the current again, you will reach a point **e** where there is zero flux density, (similar to point **b** previously)
8. Finally, you would have to **"coerce"** the core back down to zero flux density at point **f**.
9. From there, you will be going back to point **a** all over again, and repeat the process.

This is a very significant finding, because what it means is that the area inside the **BH loop** represents the amount of energy required to magnetize, demagnetize, and finally to re-magnetize the sample. Although this energy is very small, if it is repeated many times per second it can begin to represent a measurable amount of energy. This explains why most electrical machines get warm with use. It also explains why automobile tires get hot as they roll down the highway, continually flexing the rubber as they go. So you see that magnets are not the only things which exhibit **hysteresis.**

The Fundamental Relationship Between Electric Currents and Magnetism
The above text will hopefully have explained that electric currents and magnetism are fundamentally inter-related. By this we mean that an electric current in a wire (or a coil of wire) will induce a corresponding magnetic field.

Practical Applications

DC applications. One of the most common and practical application of a magnetic circuit which does not vary with time (direct current, or DC), are the large **electro-magnets** which are used in scrap yards and steel mills etc., to pick up large pieces of metal. Then when the current is switched off, the metal is released and falls to the ground. **Note here** that only magnetic metals can be picked up this way. Aluminum and copper etc., being non-magnetic, cannot be so handled.

AC applications. Currents which change in magnitude with time are known as "alternating currents", or AC for short. AC applications are almost too many to mention. Virtually all electrical equipment in use today are based in some way or another on alternating voltages and/or currents. There are additional related lesson plans available in this series – **Basic Electric Transformers, Basic AC Motors, and Basic DC Generators and Motors.** The reader is invited to refer to these for further information.

BASIC ELECTRIC CIRCUITS

Ohm's Law (and all that Jazz)
Electricity is funny stuff. You can't see it and you can't smell it. But you sure can feel it if you touch it. So **BE CAREFUL!**

For the beginner, the easiest way to visualize what goes on in an electrical circuit is to think of it in terms of water flowing down a pipe. In the first instance there are only three essentials to the understanding of electricity using this analogy. These are:

Pressure, which in electricity is measured in **Volts.** The abbreviated symbol is **V**. Because **Voltage** in an electrical system is very similar to pressure in a water pipe, in the early days of the industry, 100 years ago, it was common to see statements such as "…the pressure in the line was 200 volts…" The term commemorates the name of one of the very early experimenters in this field Alessandro Volta of Italy, 1745-1829.

Speed of flow, or **current**, which is measured in **Amperes, or Amps** for short. The abbreviated symbol is **A. Current** in an electrical system is very similar to the speed with which water flows in a pipe. In water, the speed of flow is in gallons per minute. In electricity, the speed of flow is measured in **Amperes.** This unit commemorates the early French experimenter, André-Marie Ampère, 1785-1836.

Resistance, (equivalent to Friction) to current flow, which is measured in **Ohms.** The abbreviated symbol is **Ω**, which is the Greek letter Omega. However, because it is such a short word, it is usually written right out as **Ohm**. The **Resistance** to the flow of electric current is analogous to the friction which slows down the speed of flow of water in a pipe. The term, **Ohm**, is named after Georg Ohm of Germany, 1789-1854.

OHM'S LAW

There is a very simple relationship between these three terms, which taken together is known as "Ohm's Law". In words, this is expressed as:-

	Volts ÷ Amps = Ohms
Or putting it another way:	**Volts ÷ Ohms = Amps**
Or again:	**Ohms ÷ Amps = Volts.**

However, monosyllabic mathematicians being what they are, they have further abbreviated it as follows:-

Volts is written as:	**V**
Current in written text is:	**A**
But current in a mathematical expression is written:	**I** (Some people can be difficult.)
And Ohms are written as:	**Ohm**

What all this means for example is that if you double the volts in a circuit of a given resistance, the current will double.

Or if you double the resistance in a circuit, either the current will drop to half, or you will need to double the voltage (pressure) to maintain the same current flow.

There are some excellent and more detailed explanations in Wikipedia of how these units were derived and how they are used. But for the purpose of this beginners' lesson, what this all boils down to is extremely simple. Just say to yourself **"Volts over Amps equals Ohms"**, and you will never go wrong! The author of these notes has been saying this to himself for over 60 years, and he gets it right every time. Guaranteed!

Some Offshoots of Ohm's Law

Power (Speed of Energy Flow). The above relationship between volts, amps and ohms is really just a starter. The next thing we need to consider is what happens if we leave the current flowing for any length of time? Well, the chances are that things will get warm, or maybe even hot. So we need to know how much heat is flowing. The speed, or more correctly, the **rate** at which energy is flowing from one point to another is measured in **Watts**. Curiously, this unit is named after the Scottish pioneer of steam engines, James Watt, 1736 – 1819, who had nothing to do with electricity. It is calculated by multiplying the "pressure" in volts times the speed of current flow in amps. For the benefit of doubters, this is strictly analogous to the number of pounds of steam sent down a pipe in a given time.

But if we go back to the Ohm's Law relationship above, and rework things a little, we come up with the following interesting things which are also worth memorizing.

For starters, **Watts** = **Volts** x **Amps**. (By definition).

But since Volts = Amps x Ohms, it follows that
Watts = Amps x Amps x Ohms,

Or **Watts** = **$(\text{Amps})^2$ x Ohms**

And unfortunately, here we get into another confusion, because quite often instead of writing the word "resistance", we use a short-hand of **R**. You will just have to get used to it!

And written another way, it becomes: $\mathbf{W = I^2R}$

This is a very important relationship, because it means that, all other things being equal, if you increase the current by 50%, the heat increases by a factor of $1.5^2 = 2.25$. Or going one stage further, if you double the current, the heat will increase by a factor of 2x2=4. What this really amounts to is that if you increase the current by even a small amount, your equipment can get really hot in no time at all.

Students are strongly urged to use this expression because you will frequently hear an expression such as **"… the I squared R losses are really high on that one…"**.

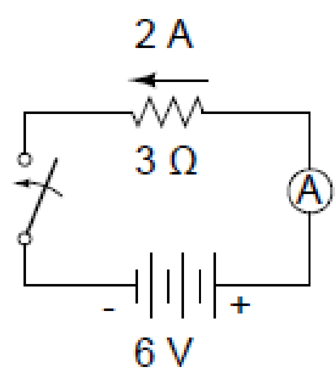


Fig. 10

Circuits and Symbols

At this stage, it will be useful to look at a few simple circuits and see what they mean. In Figure 10, there are only four components, a 6 V battery, a switch, a resistor of 3 Ω, and an ammeter to measure the current.

The Battery. There are many types of battery, but in the interest of simplicity, we can examine just three here.

1. The first is the small non-rechargeable type as used in flashlights. These are known as "alkaline" cells and produce **1.5 Volts** each. If you want more voltage you can connect two or more in series as required. (See below). For reasons which will be explained later, they can only produce a very small current flow (maybe less than one

amp). They are cheap and compact, but have to be thrown out when discharged. (Please send them to the hazardous materials collector).

2. The so-called "Lead-Acid" type such as are used in automobiles. Because of the chemical reaction inside (not discussed here) these can be recharged when their voltage runs down. When fully charged, each cell produces **2 Volts.** Hence in an automobile, which uses a 12 Volt system, you will see six individual cells all within a single black plastic casing. Because they contain lead, they are very heavy. But they are amazingly robust and can produce very high currents required for starting the engine. (Several hundred amps are common, but only for two or three minutes). They are also comparatively expensive. Safety Note: Automobile batteries contain sulfuric acid and should under no circumstances be taken into the classroom.

3. For the sake of demonstrating an awareness of current technology, it is worth mentioning the "Lithium-Ion" battery. These contain Lithium, which is an expensive metal similar to Sodium. (Sodium, as you may know, is quite light and can be cut with a knife. Sodium burns fiercely when put in water, and is therefore quite unstable). Lithium is much the same. Lithium-Ion batteries produce 3.5 Volts per cell and are therefore favored where weight is a consideration, such as lap-top computers and aircraft. As most students will know, over the last couple of years there have been several spectacular instances of fires in both computers and large commercial aircraft using Lithium Ion batteries.

4. For simplicity, it is assumed in Figure 5 (Page 8) that there are 3 cells of 2 Volts each, making 6 volts total.

5. Note that by convention, the negative end of the cell is shown with a negative sign **–** while the positive terminal is marked with a **+**. By convention (dating back probably to the days of Ampère), the current is assumed to flow out of the positive terminal, through the circuit and back to the negative terminal. It was only much later, when electrons were discovered, was it realized that the flow is actually the other way round. But by then it was too late, and the convention was too well established to be changed. But it is as well to keep this small fact in mind.

The Switch. S is the standard symbol for a switch. This one is just a simple open and shut device.

The Resistor. R is the standard symbol for a resistance. In this case it is 3 Ohms.

The Ammeter. A is the standard symbol for an ammeter, which is to measure the current in amps.

CIRCUIT ANALYSIS

With the switch open as shown as shown in Figure 11, no current can flow. Note however that there will be a voltage of 6 Volts across the two terminals of the switch. With the switch **closed**, current will flow. Using the Ohm's Law above we can make the following calculations.

- Current, **I** will be "Volts/Ohms" = 2 amps.
- Power, **W** will be I.R = 2 x 2 x 3 = 12 Watts

A Series Circuit

In Figure 11, we have added a second resistor of 2 Ω. Hopefully it will be self-evident that the total resistance is now 5 Ω, and that,

- Current is now **V / R** = 6volts÷5 Ohms = 1.2 Amps.
- Power, **W** will be I.R = 1.2 x 1.2 x 5 = 7.2 Watts.

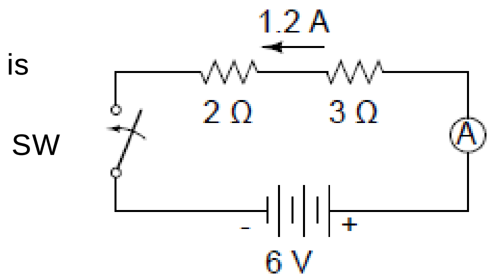


Fig. 11

A Parallel Circuit

In Figure 12 we see two resistors side by side. This will require a little more thought. Look at it this way.

- The upper resistor has 6 Volts applied to 2 Ω. So the current will be 6÷2 = 3 amps.
- The lower resistor has 6 Volts applied to 3 Ω. So the current will be 6÷3 = 2 amps.
- Therefore total current read by the ammeter is 2+3 = 5 amps.
- Now what do you suppose would be the resistance of one single resistor which would allow 5 Amps to pass? Ask Mr. Ohm about that and he would mutter "Volts over Amps = Ohms. Why! That must be V/A = 6÷5 = 1.2 Ohms. Yes?"
- Now here's the clever bit. Supposing we juggled the numbers a little, turned them upside down, and said:1÷ 2 = 0.5, and 1÷3 = 0.333. Add them together and you get 0.8333. (These are not Ohms but just numbers)[1]. But turn 0.8333 upside down once more and what do you get? Why 1.20 Ohms of course, which is what we got before. You may want to practice this a couple of times until you have got the hang of it. It is known as **taking the reciprocal.** Ask your math teacher about that. But figuring it out the first way is good enough if you are stuck. And what's more both methods work fine for any number of parallel branches – not just two as here.

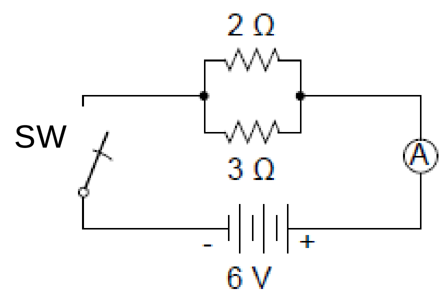


Fig. 12

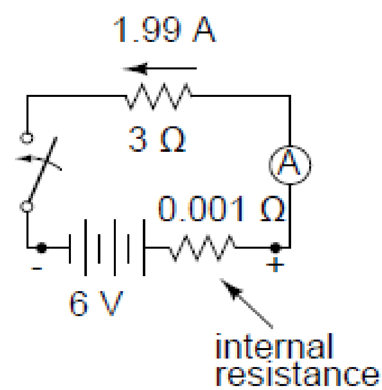


Fig. 13

Short-Circuits and the Internal Resistance of a Battery

Return for a moment to Figure 13. Let us suppose for a moment that the resistance shown there is not 3Ω, but 0.3Ω. When the switch is closed, the current would be 6V ÷ 0.3Ω = 20 Amps. A big increase. So then let us carry the matter a stage further and assume the resistance is only 0.03Ω. Then the current would, in theory, be 6÷0.03 = 200

[11] Actually an Ohm turned upside down is known as a Mho. But that's another matter.

Amps. This of course would be a huge current and probably far more than the wires in the circuit could carry. In which case the wires would get so hot they would melt. And remember that the power, (in Watts) is proportional to the square of the current ($W=I^2R$ remember?). This would be what is known as a **Short Circuit** and can be very dangerous. In a real life situation there is usually some very small, but still significant amount of resistance remaining in the circuit. But nevertheless short circuits are usually very damaging and are to be avoided at all costs. Consider now Figure 8. Note that this is a refined version of Figure 5, the difference being that it includes an additional small resistance **inside** the battery itself. This is known as the internal resistance of the battery. In the case of non-rechargeable alkaline batteries the internal resistance is always relatively quite high (several ohms in fact) so that even in the case of what is known as "a dead short circuit" (i.e., absolutely zero resistance) in the system outside the battery, the so called "short circuit current" can never be so high as to cause damage or injury. However, the case of a lead-acid automobile battery is very different. Because the lead itself is such a good conductor of electricity, the internal resistance is very low – probably of the order of a small fraction of an ohm. From what we have seen above, therefore, if the circuit outside the battery is suddenly subjected to a short circuit, the so called "fault current" can reach really high figures. In the case of an automobile battery, for example, currents can reach several hundreds of amps. More than enough to melt everything in sight. As noted on page 14 above, automobile batteries should never be brought into the classroom.

BASIC CAPACITANCE

A Definition of "Capacitance"

An easy way to think of a "capacitor" is **a device which can store very small amounts of electrical energy for a very short time.** It should **NOT** be confused with a battery, which can often store very large amounts for long periods. While the characteristics of "capacitance" are fundamentally different from those of magnetism, there is one aspect which they both share in common, and that is they are both visualized as producing a "field" of electrical effects. See Figure 14. As we have seen above, just as we speak of a magnet having a certain "magnetic field strength", which can be measured but not seen, so also we speak of an "electrostatic field", which also can be measured but not seen. However, an electrostatic field produces only a very weak field, capable only of attracting small particles of dust etc. So there the similarity with a magnetic field ends. To be more specific, if for example, a small capacitor is connected to a 6 volt DC source, and then disconnected from that source, the capacitor itself will continue to hold it's "charge" of 6 volts for several minutes. Eventually however, the "charge" will leak away and return to zero. And if you try to light even a small flashlight bulb with it, the bulb will die out in just a few seconds.

The Unit of Capacitance

The units used to describe the strength of an electrostatic field are completely different, and in fact are expressed as "Volts measured over a certain distance", usually "Volts per inch" or "Volts per cm". Most scientific measurements use the cgs (centimeter, gram, second) or metric system. It is by far the easiest way of doing small sums in your head!) The international unit for measuring the (electrical) size of a capacitor, is the **Farad**, after the English scientist, Michael Faraday, 1791 – 1867.

Probably the easiest way to visualize an electrostatic effect is to take a very small piece of paper the size of your little finger and lay it on the table. Then rub a plastic pen or other (non-magnetic and non-conducting material) and rub it briskly against your sleeve. With any luck, you will be able to pick up the piece of paper. Another illustration is to note how, when you take off a nylon sweater it tends to cling and to make your hair stand on end. It also makes a slight crackling noise. These effects are mostly more evident in winter, when the air is dry. And there is a reason for this, which is that when the air is moist, the small particles of water in the air are slightly conducting, and tend to "short circuit" or bypass the electrons between the paper and the plastic pen.

The principal characteristics of a capacitor are:

1. Capacitance is directly proportional to the surface area of the two surfaces. The bigger the area, the bigger the number of "farads" in the capacitor.
2. The capacitance also increases as the two plates become **closer** together. This of course is a problem, because if they become too close, (like a thousandth of an inch) the chances are that the two plates will touch. If that happens, even for a miniscule particle of grit – then you will get a short circuit and there will be no capacitance at all. So that becomes a quality control problem.
3. Conversely, the further they are apart, the capacitance **becomes less**.
4. For the really small capacitors found in electronic circuits (usually small brown blobs) the materials are dipped in epoxy to give them physical strength. For the much larger industrial capacitors the sheets of aluminized paper are usually rolled up into a sort of sausage and put into an hermetically sealed steel or aluminum casing filled with thin oil. The advantage of capacitors is that they are cheap, have no moving parts and are therefore robust. If they fail, they cannot be repaired and have to be recycled.
5. Capacitors do not display "Polarity" in the way that magnets do. In other words, it makes no difference which terminal of the capacitor is connected to the **+** of the supply and which to the **–** . It will work equally well either way.
6. The most common construction of a capacitor is to take two sheets of thin brown paper, both of which are coated with an equally thin layer of aluminum foil. These sheets are then rolled up together soaked in light mineral oil and hermetically sealed into a steel can. One lead from each of the two layers of aluminum foil, are of course, brought out through the can, to serve as external connectors.

What can a Capacitor Do?

Figure 14 represents a simple capacitor. It comprises two thin metal plates separated by a material which has a very high resistance. Let us assume for the moment that this resistance is 1 million ohms. From what Mr. Ohm has already told us, the current which would flow when you apply 6 Volts to 1,000,000 ohms will be vanishingly small. As a matter of interest plain brown paper soaked in oil is the most common insulating material, (called the **Dielectric**). It is cheap, effective and reliable. In Figure 14, switches $\mathbf{SW_1}$ and $\mathbf{SW_2}$ are mechanically linked together in such a way that while both can be open at the same time, only one of them can be closed at the same time. Thus if SW_1 is closed first, voltage from the battery will flow into the capacitor until the voltage across the capacitor plates is equal and opposite to that of the battery. But because the resistance of the **dielectric** is so high, the current will be virtually zero, and once the capacitor is fully charged, no further current will flow. And then if SW_1 is opened, and if the dielectric is of good quality, the 6 Volts across the terminals of the capacitor will remain for some considerable time, like, say, 10 - 15 minutes. Eventually, however, the voltage will gradually leak away. But even with lesser quality dielectric, the average capacitor will "hold its' charge" for maybe 5 minutes or so, before it leaks away.

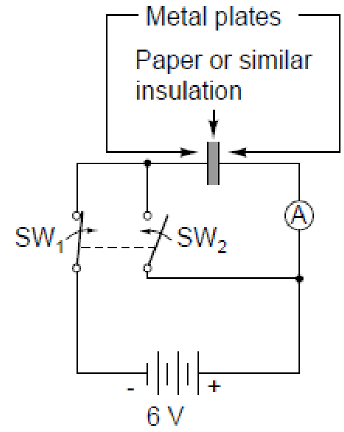


Fig. 14

Then if SW_2 is closed, a short circuit is formed across the capacitor, and the 6 Volt charge collapse almost instantaneously. Certainly so quickly that the ammeter A will hardly have time to register, and will merely flicker. Certainly no meaningful amount of power (measured in watts) will be involved. But once it is discharged, the process can be repeated over and over again. This is what we mean when we say that a capacitor can store very small amounts of energy for very short periods of time. And let us not forget that since a capacitor has no moving parts, it is robust and with a long working life (measured in decades if properly treated).

What can capacitors be used for? Capacitors have thousands of applications. They can be found by the dozen in computers and other electronic devices. Little things smaller than the nail on your little finger. In such applications, the very small amounts of electricity they can store for a short time are at the same level as the other electrical signals travelling around any printed circuit board (PCB). On a larger scale, if you have a vacuum cleaner motor which is not in good shape and is sparking inside, making a hiss on the radio, this can be "suppressed" by adding a suitable capacitor across the terminals. And that is exactly what it does. Instead of allowing the (very small) energy in each spark to radiate off and make the radio hiss, the capacitor absorbs the energy in the spark and then releases it again back into the motor when things go quiet, many thousands of time per second. (That said, it would probably be better to have the vacuum motor repaired).

Moving up in size again, capacitors are used in huge quantities in high voltage power systems, but that's another story.

The ability of a capacitor to hold a charge at quite high voltages for 10-15 minutes brings with it a safety consideration, which applies not just in a school classroom but in "real life" also. It should be noted that some capacitors in older style CRT TV sets for example, operate at voltages in the hundreds of volts or more. Voltages of these magnitudes can give even an adult a significant jolt. Capacitors of this type are usually equipped with a suitably chosen resistor which can discharge the unit after a set time. But as a general safety precaution, it is good practice to make sure a capacitor is discharged before touching it. This can safely be done by shorting the two terminals together with a screwdriver provided it has a plastic handle.

Is there an Application for Electrostatic Electricity?
It has to be admitted that every-day applications of electro-static electricity, (as opposed to capacitors) are much fewer than there are for electro-magnets. If you refer back to the first section on electrostatics above, you will recall that we cited the case of rubbing a piece of plastic on your sleeve, and then picking up a very small piece of paper. So there you have it. Electrostatic electricity is very useful for picking up very finely divided particles such as dust and powder etc. A practical instance is that of large electric generating plants which burn coal as a fuel. The smoke which goes up the chimney usually contains large amounts of burned coal dust and ash. These are a major pollutant and health hazard. But they can be relatively easily collected if the smoke is passed between a pair of large electrostatically charged plates before it goes up the chimney. (And what's more that dust can be sold for a fair commercial price and added to concrete mix where it helps the concrete set more quickly).

But how would you generate the Electrostatics?
If you look into many text books, you will see a machine called a **Van der Graaff** machine (yes, that's the spelling). This is a very simple device and comprises a continuous loop of synthetic ribbon which passes over a smooth metal "shoe". In demonstration units, the ribbon is continuously driven by a small electric motor, such as that inside an electric toothbrush. Surprising as it may seem, the voltage produced by such machines can reach very high values, often several thousand volts. It is therefore not generally used in for classroom demonstrations. But there some very good descriptions of it on the net. As a side note here, and despite what one might think from the name, it is a comparatively modern American development, dating from 1929.

ELECTRIC SHOCK AND BASIC SAFETY PRECAUTIONS
At this point it may be as well to briefly touch on the matter of electric shock, because Ohm's Law applies here also. Note the following:

- The resistance measured between both hands outstretched of an average adult male is about 10,000 ohms
- The resistance measured between both hands outstretched of an average adult female is about 8,000 ohms.
- These figures vary widely but will serve for this discussion.
- Small children are of course much lower.

- Experience has shown that a current as low as 2 milli-amps (2÷1,000, or 0.002A) can give an adult an unpleasant jolt. Currents above 5 milli-amps can make it difficult to let go, and at 25 milli amps the heart tends to lose its heartbeat. These currents can be fatal because in travelling from one hand to the other, they pass through the heart, which is very sensitive.

- Suppose for example a person with a resistance of 8,000 ohms touches a faulty domestic appliance at 120 Volts, Ohm's Law tells us that the current could be 120V ÷ 8,000Ω = 0.015 amps, or 15 milli amps, which is already half way to the level at which the heart begins to fail. Fortunately, household electricity is alternating current (AC), which has a tingling effect which tends to make the victim want to let go. Direct current (DC) on the other hand, tends to make the muscles contract and hold on tight. (See our friend Galvani on page 1). DC is therefore rather more dangerous. But fortunately it is less common. The National Electrical Code requires that any appliance which can be held by hand, such as in kitchens and bathrooms etc., be fitted with a "Ground Fault Protector", a sensitive device which cuts off the voltage if it detects a problem.

- **But these figures show that you can't be too careful.**

What is Insulation?
The term "insulation" is what we use to protect wires from touching each other and causing a short circuit. At the beginning of this lesson, we used the analogy of electricity in a wire behaving in a manner similar to water in a pipe. In the case of "insulation" this analogy again holds true.. Look at it this way. If the water pressure becomes too high, the pipe bursts. So in the case of electricity, if the voltage (pressure) becomes too high, the insulation will "break down" and cause a short circuit. Insulation is primarily used for two main purposes.

- To prevent users of electrical equipment from touching the "live" parts and (if the voltage is high enough), getting an electric shock.

- It is also used to make sure that the various parts of a circuit do not accidentally touch each other and either give false results, or in the worst case, cause a short circuit. And of course, our old friend Mr. Ohm and his law apply in much the same way. In fact it applies even more so. Joking aside, we mean that whereas in a small circuit, the resistance may be only a few ohms. In the case of insulation, we measure it in thousands or even millions of ohms.

- Take the case of a domestic appliance for example. The voltage applied is either 120 Volts or 240 Volts as the case may be. In order to limit the current through the insulation to as close to zero as possible, we should have say 1 million ohms, or what is usually called 1 Megohm.

- Hence 240 Volts÷1,000,000 ohms = 0.00024 amps, or 0.24 milliamps.

But as we have seen above, even this is not really enough, so we should be looking at an insulation resistance of, say, 10 Megohm, to be safe, since this would reduce the “leakage current to 0.024 milliamps. And that is milliamps, or 0.000024 amps.

So there’s another buzz word for you. Always think of insulation in terms of **megohms**.

Some Good Insulating Materials

Glass, Rubber, Some PVC plastics, Mica, Electrical varnish, Porcelain China, Epoxy Resin Specially treated paper immersed in specially treated mineral oil. But only for items which do not move.

COMMONLY ENCOUNTERED UNITS OF ELECTRICAL MEASUREMENT

Mega Million (Volts, Amps, or Watts as the case may be). **M**

kilo Thousand. **k**
(Note this must be a lower case “k”, because upper case K is used for Kelvin, a specialized unit of temperature.

milli 1/1,000 or 0.001 or one thousandth. **m**

micro 1/1,000,000 or one millionth. **µ**

Pressure	Volts	**V**
Current	Amps	**A**
Power	Watts	**W**
Resistance	Ohms	**Ω**
Insulation	Megohms	**MΩ**
Capacitance	Farads	**F**

(Note: In actual fact, a Farad is a very large unit, and it is customary to use a very much smaller unit, a micro-Farad or µF, which is, of course one millionth or 0.000001 Farad).

For Teachers:
Teacher Resources

HANDS-ON ACTIVITIES

1. For a **Magnetism** hands-on, some iron filings and a bar magnet as shown in Fig.1 can be used.
2. Try also suspending the bar magnet **horizontally** by a piece of string and hang it from a door frame. Does it eventually point approximately North-South?.
3. Another inexpensive demonstration of **Electromagnetism**, obtain a small, empty, plastic pill bottle and wind maybe 300 turns of #30 awg magnet wire around the outside. Place a small button magnet inside and close the cap. Connect an LED (cost $2.00) to the two ends of the wire and shake the bottle. The LED should light up..
4. For a classroom exercise dealing with **Ohm's Law**, it is suggested that students be given a range of different numbers relating to Figures 5, 6, and 7, and asked to calculate the currents and/or resistances resulting from these.
5. As second demonstration of **Ohm's Law** could be a small flashlight battery, a flashlight bulb and two short lengths of wire. By connecting the two together, the bulb will light up. Then when the circuit is broken, the bulb will go out. This is sufficient to demonstrate that electricity only flows when there is a continuous path, from the positive terminal, thorough the circuit and back to the negative terminal.
6. Does a **Capacitor** hold a small amount of energy for a very short period of time? Obtain three LEDs, ($2.00 each) and a large capacitor. One rated at10,000 µF and 10-20 Volts would be suitable ($5.00). The LEDs are rated at 2.2 V each, so connecting them in series will enable them to withstand 6.6 volts. But they are delicate, so buy a few spares. Connect them across a 6 V lantern battery. They will light up nicely, but as soon as the battery is disconnected, they go out in an instant. Then connect the capacitor to the battery also. The LEDs will flicker briefly as the capacitor "charges up" to 6 V, and then resume their original brightness. Then disconnect the battery but keep the capacitor connected to the LEDs. You will find that for maybe 5 or 10 seconds, the LEDs remain bright, before gradually dimming down to a dull glow as the capacitor discharges through them. But they do not go out completely. LEDs consume very little energy, but nevertheless this does demonstrate that capacitors can indeed store equally small amounts of energy. You will also find that the capacitor alone, without the LEDs, will retain between 4.5 and 5 volts for 5 or 10 minutes or more. Figure 15 shows a simple set-up. The above demonstration is extremely inexpensive. The LEDs cost about $2.00 each and the capacitor about $5.00. Total $11.00. And everything is re-usable.

Fig. 15

Student Worksheet:

◆ **Reflection**

Complete the reflection questions below:

1. Suppose your battery goes flat. What would happen to (a) the resistor, and (b) the current?

2. In the above demonstration, you have covered the bar magnet with a sheet of paper and then sprinkled iron filings over it to show the lines of magnetic force. What would have happened if you had used particles of copper?

3. Did you make enough iron filings?

4. Why is a Van De Graaf generator not suitable for use in a classroom?

Basic Electricity and Magnetism

For Teachers:
Alignment to Curriculum Frameworks

Note: All lesson plans in this series are aligned to the National Science Education Standards which were produced by the National Research Council and endorsed by the National Science Teachers Association, and if applicable, also to the International Technology Education Association's Standards for Technological Literacy or the National Council of Teachers of Mathematics' Principals and Standards for School Mathematics.

◆National Science Education Standards Grades 5-8 (ages 10 - 14)

CONTENT STANDARD B: Physical Science

As a result of their activities, all students should develop an understanding of

- Motions and forces
- Transfer of energy

CONTENT STANDARD F: Science in Personal and Social Perspectives

As a result of activities, all students should develop understanding of

- Science and technology in society

CONTENT STANDARD G: History and Nature of Science

As a result of activities, all students should develop understanding of

- History of science

◆National Science Education Standards Grades 9-12 (ages 14-18)

CONTENT STANDARD A: Science as Inquiry

As a result of activities, all students should develop

- Abilities necessary to do scientific inquiry
- Understandings about scientific inquiry

CONTENT STANDARD B: Physical Science

As a result of their activities, all students should develop understanding of

- Interactions of energy and matter

◆Next Generation Science Standards – Grades 5-8 (Ages 10-14)

Motion and Stability: Forces and Interactions

- MS-PS2-3. Ask questions about data to determine the factors that affect the strength of electric and magnetic forces.

Energy

- MS-PS3-2. Develop a model to describe that when the arrangement of objects interacting at a distance changes, different amounts of potential energy are stored in the system.

◆Standards for Technological Literacy - All Ages

Technology and Society

- Standard 7: Students will develop an understanding of the influence of technology on history.

Design

- Standard 10: Students will develop an understanding of the role of troubleshooting, research and development, invention and innovation, and experimentation in problem solving.

The Designed World

- Standard 16: Students will develop an understanding of and be able to select and use energy and power technologies.