



# Basic Electricity and Magnetism

## "But it's the Law, Doktor Ohm!"

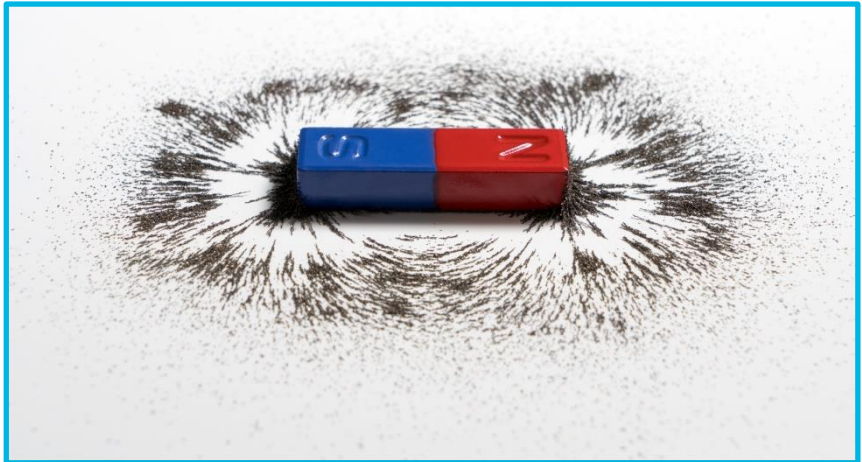
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### Lesson Focus

This lesson focuses on the basics of electricity and magnetism. 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.

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## 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 electromagnetic field could be harnessed to other purposes. From there the lesson goes on to demonstrate how electric currents, magnetic fields and electrostatic 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.

### Helpful Suggestion:

This lesson contains a relatively large amount of supplementary technical information. As a result, it is a little longer (36 pages) than some of the others in this series. Since most students these days have access to the internet, it is suggested that they be encouraged to read the text by themselves, either before the lesson is delivered in class, or at home afterwards

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## 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.

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## 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.

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## Anticipated Learner Outcomes

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

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

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### **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.

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### **Resources/Materials**

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

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### **Alignment to Curriculum Frameworks**

- ◆ See attached curriculum alignment sheet.

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### **Internet Connections**

- ◆ TryEngineering ([www.tryengineering.org](http://www.tryengineering.org))

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### **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.

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### **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.

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### **Source**

- ◆ This lesson contributed to TryEngineering by Dave Hepburn, IEEE Canada.

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## For Teachers: Teacher Resource

### ◆ Lesson Goal

The "Breadboard Circuitry" lesson explores the use of breadboards to help students understand basic circuitry without soldering.

### ◆ Subjects Covered

- ◆ The Origins of Electricity
- ◆ Basic Magnetism
- ◆ Electromagnetic Induction
- ◆ Hysteresis
- ◆ Ohm's Law
- ◆ Simple Circuits
- ◆ Capacitance

### ◆ Materials and Costs

To all intents and purposes, the material costs for the demonstrations in this lesson are very modest. A few dollars at the most, and some items can be re-used several times over. Bronze washers cost about 50 cents each and bar magnets are available on line at stores which sell science supplies.

### ◆ Safety

Magnets and flashlight batteries are, of course perfectly harmless. However teachers should be made aware of the fact that automobile batteries can be extremely dangerous. For one thing, they contain sulfuric acid which can cause bad skin burns, and indeed if splashed into the eyes can cause permanent blindness. For another thing, these so-called "Lead-Acid" batteries are designed to start car engines even in very cold weather and can provide as much as 200 amps of current, even at 12 volts. They can therefore cause serious thermal burns if not treated carefully. Also, these types of batteries also give off hydrogen, which is explosive. Lead-Acid batteries should therefore never be brought into a classroom.

### ◆ 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.

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**For Teachers:**  
**Teacher Resources (continued)****◆ 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 actually only flew the kite close to the thunder cloud. 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 just 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 the static 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 thick paper soaked in salt water, he could produce a reasonably steady and readily available source of electricity.

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.

What Volta did early in the year 1820 (after much trial and error) was to take a series of 15 copper discs and 15 zinc discs, divide them into pairs (one of each) with a disc of thick paper between them. But first he soaked the paper discs in a saturated solution of ordinary

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table salt. He then piled all the discs vertically in a light frame to clamp them down lightly to prevent them from falling over. The original of this device is in a museum in Italy, but you can see a photo of it on the net under the heading of Alesandro Volta. The exact number of discs is difficult to tell from the photo, and of course in 1820 there was no means of measuring the strength of his "voltage". In fact the term itself was not adopted until much later. The net also seems to be quite coy as to how Volta came to realize that his device could actually produce an electrical current. One source simply says that he deduced it on the basis of what he had observed in his other experiments - but that doesn't help much. The author of these notes speculates that he applied a "frog's' leg" test. Who knows? See Figures below.



Figure 1

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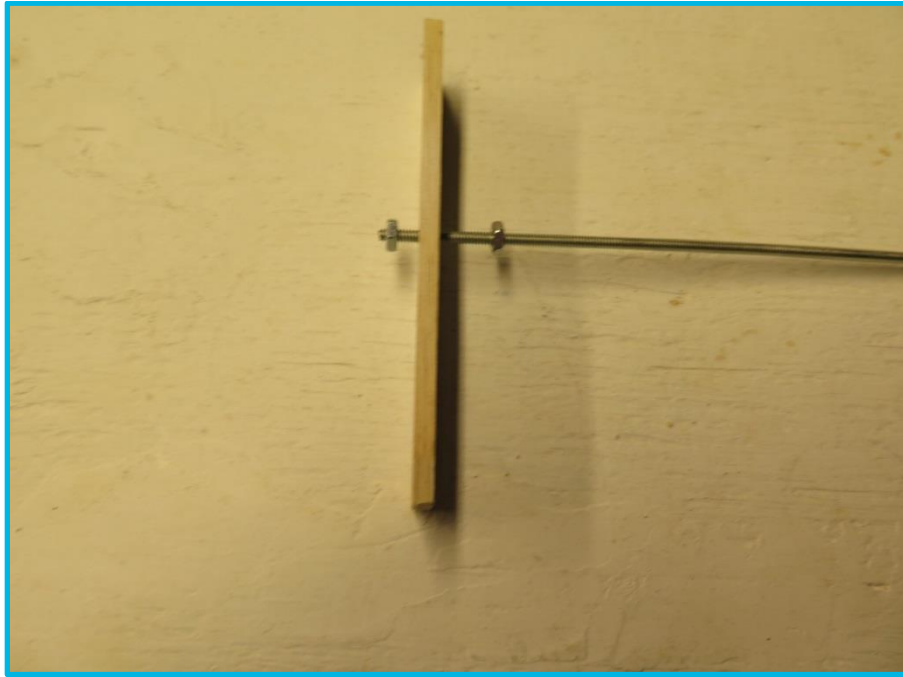


Figure 2

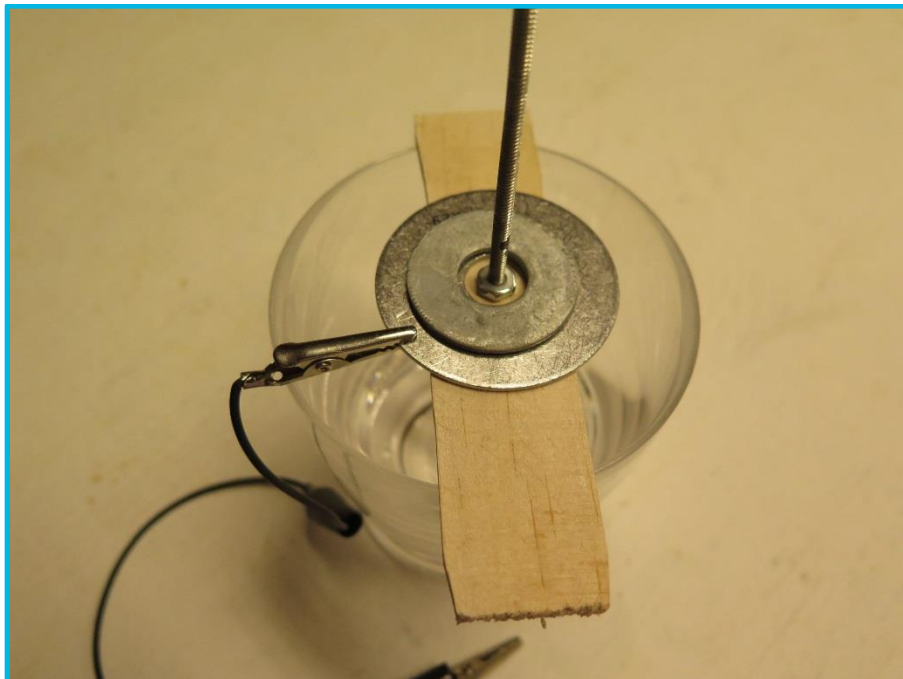


Figure 3

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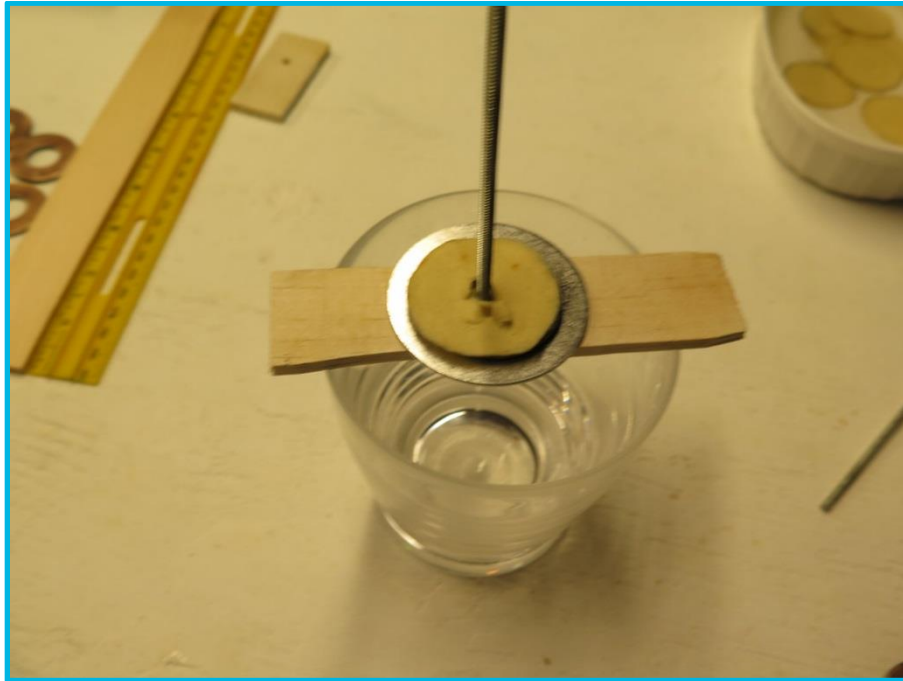


Figure 4

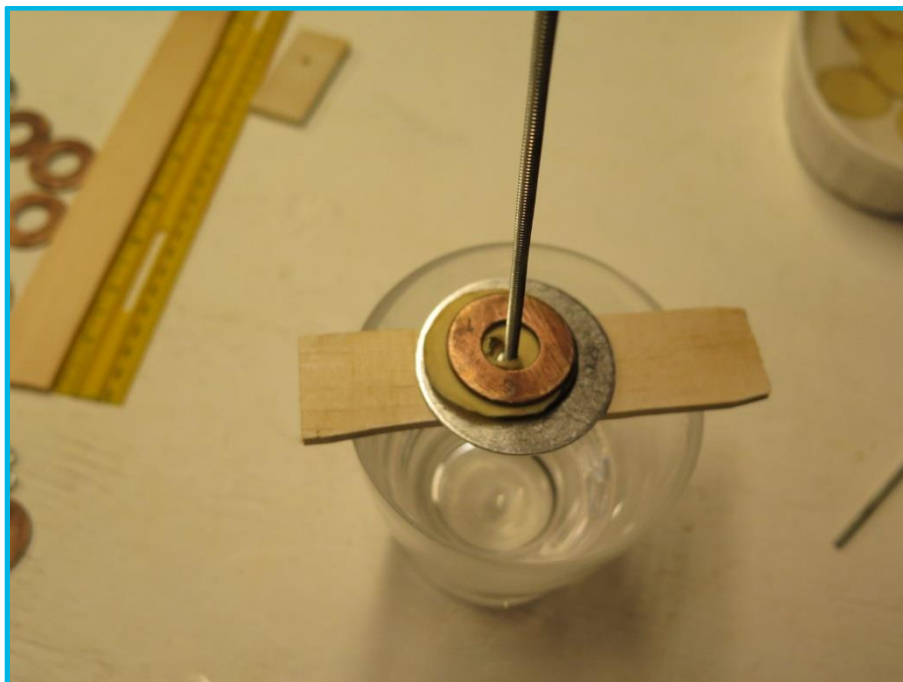


Figure 5

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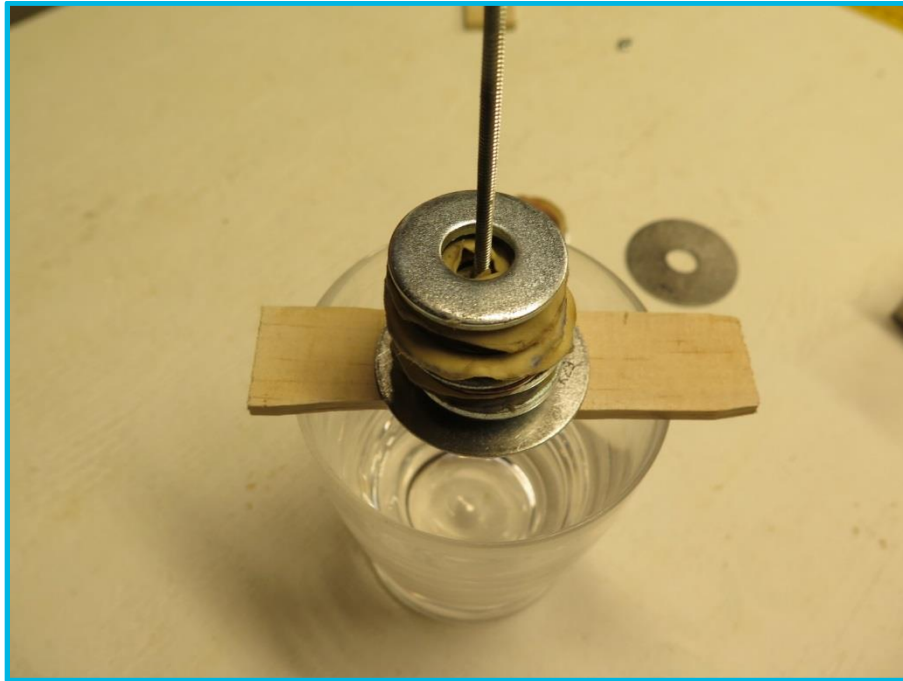


Figure 6

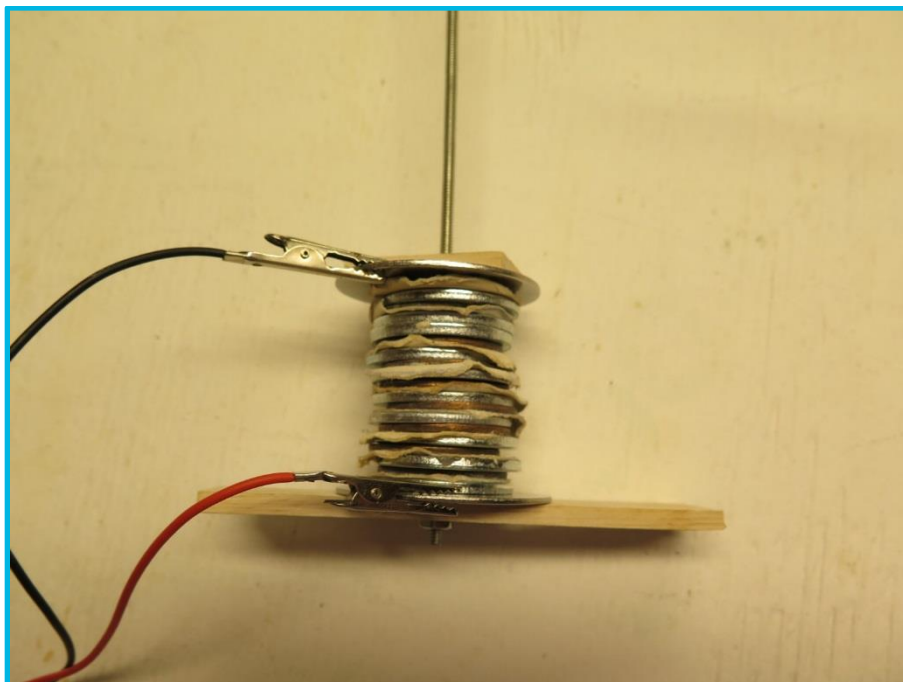


Figure 7

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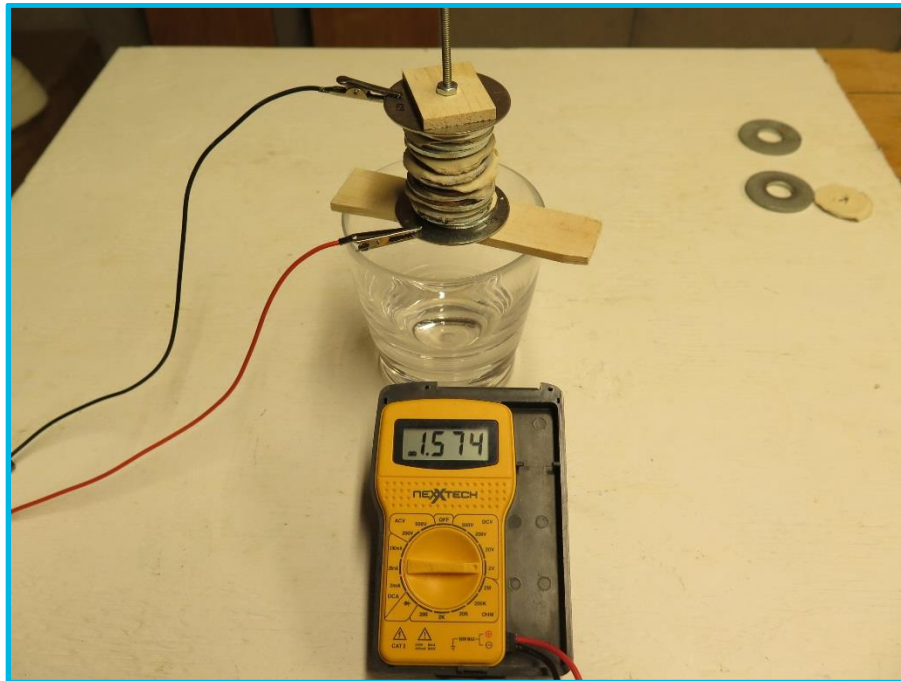


Figure 8



Figure 9

Things get rusty pretty quickly when there is salt water about!

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**For Teachers:**  
**Teacher Resources (continued)**

◆ **Two Class Challenges**

**First:**

1. Nevertheless, what Volta did in his original experiment is comparatively easy to replicate in the classroom, as shown in Figures 1 – 9 above, and for very little cost.
2. Obtain 10 galvanized steel washers about 1-1/2" (about 3.5 cm) diameter. These cost about 10 cents each. The galvanized coating is actually a wafer thin layer of zinc, which is good enough for our purpose although it soon wears off.
3. Obtain also, ten bronze washers, also 1-1/2" diameter. Bronze is usually 95% copper and 5% tin, but again that is good enough for our purpose. Bronze washers of this size cost about 50 cents each, or \$5.00 total.
4. Obtain, also 2 larger steel washers, say 2-1/2" (6 cm) diameter. These are simply to serve as something substantial for the alligator clips to get a grip on.
5. Divide the class into teams and have them cut ten paper washers, likewise 1-1/2" diameter. An old file folder is good enough for our purpose provided it will absorb water. Plastic is not suitable.
6. Soak the paper washers in a saturated solution of salt water. If you don't know the meaning of "Saturated" ask around the class.
7. Have your teacher locate a thin wooden stick of the type used for stirring paint. Most hardware stores give them away free. Ask him (ever so politely) to cut two pieces of stick each about 3" (7.5 cm) long.
8. Ask your teacher to locate a length of threaded steel rod about 1/8" (about 3 mm) diameter. In Figure 3 the rod is what is known as "#6-22". This means #6 diameter (American size) with 22 threads per inch. A standard length in the store is 12" (30 cm). This will be too long, but it doesn't matter. Leave it as it is.
9. You will also need 3 small nuts of the size to fit the threaded rod. (#6-22).
10. Assemble all these items as shown in Figures 2 to 8.

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11. The sequence is as follows.

- ◆ One very large washer.
- ◆ One galvanized washer 1-1/2: diameter.
- ◆ One paper washer soaked in salt water.
- ◆ One bronze washer.
- ◆ One galvanized washer (no paper washer between bronze and galvanized).
- ◆ One paper washer.
- ◆ One Bronze washer.
- ◆ One galvanized washer (No paper between the bronze and steel.
- ◆ Keep on going until all galvanized and bronze washers are used up
- ◆ Finally add the second large steel washer to serve as a terminal contact.
- ◆ Place the second piece of wood on top of the pile and snug it down with the small nut.

12. The finished assembly is shown in Figures 7 & 8. When fresh this gave about 2 Volts, or 0.2 Volts/pair (Cell). However, this declined after only a few hours to 1 Volt or less. This was because the zinc coating on the steel washers was so thin, it was soon eaten away by the chemical reaction. In Volta's day, his zinc discs were solid zinc and copper. His pile had 15 pairs and apparently gave 0.75 Volts/pair. Modern flashlight batteries give 1.5 V and automobile "Lead-Acid" batteries give 2 Volts/cell.

### **Some helpful tips for assembling a voltaic pile**

- ◆ It is easy to get mixed up when assembling washers with and without paper between them. Try this:-Repeat to yourself "SPB, SPB, SPB", which means "Steel. Paper, Bronze, Steel, Paper, Bronze, etc.
- ◆ There are some very helpful color diagrams on the Net, under the heading "Alseandro Volta".

### **Another class challenge (probably as homework)**

- ◆ Undertake a literature search to see if you can find what tests Volta used to satisfy himself that his device was really producing a steady flow of electricity. Remember that he had no instruments other than perhaps a magnetic compass needle.

**For Teachers:**  
**Teacher Resources (continued)**

◆ **Ongoing Research**

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.

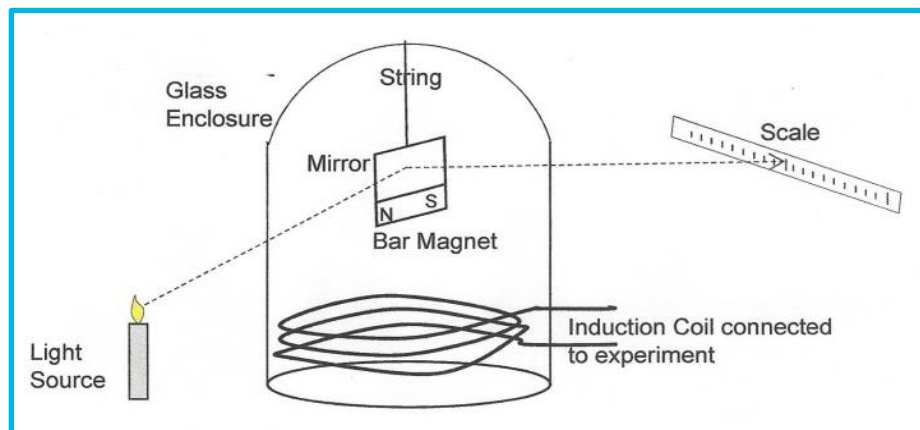


Figure 10

In Figure 10, 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.

Again, in 1820, and almost coincident with the discovery of the Galvanometer, the Danish scientist, Hans Christian Oersted (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. Oersted 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 11. Note: A 6 V battery was used here. Actual current not measured, but the wire got hot in 2 minutes.

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Figure 11

In the next year (1821) the English scientist, Michael Faraday (1791-1867) read of Oerstead's discovery. Firstly, he repeated Oerstead's experiment to satisfy himself that the compass needle really did deflect. (Faraday was VERY thorough in everything he did. 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. To his surprise, he found that the copper wire rotated at quite a high speed. And if he reversed the polarity of his battery, the rotation reversed also. This experiment cannot be demonstrated in class because Mercury is a very toxic substance. But you can see an illustration if you look up Michael Faraday on the Net. 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 in (1821).

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 12.

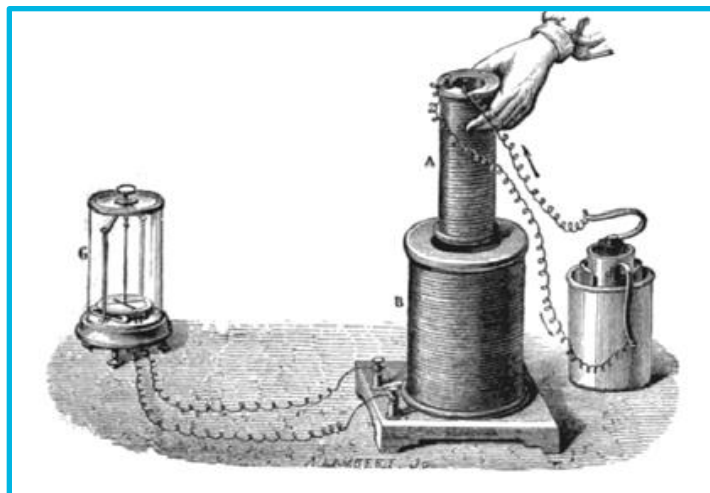


Figure 12: Concept by Faraday 1831. Engraving circa 1892 by A Lambert.  
Figure 248 in Text Book "Magnetism & Electricity" by A.W. Poyser, 1893.

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This experiment by Faraday dates from about 1831 and demonstrates his discovery that any change in the “magnetic linkages” between the lines of magnetic force in the coil in his hand as he lowered it into the main coil, and the turns of wire in that main coil, would produce a small voltage which deflected the galvanometer connected to the main coil. When the movable coil was held stationary there was no deflection, but when the coil was withdrawn, the deflection was in the opposite direction. Note: The similarity between the galvanometer and the magnetic compass shown in Figure 12 above. In effect, and presumably without knowing it, Faraday had discovered the basis of an electrical transformer. See related Lesson Plan – “Basic Electric Transformers”. The whereabouts of the original apparatus is unknown. Probably lost. But from the related text it is evident that the original coils were very carefully made on a lathe of some sort, using many hundreds of turns of thin copper wire insulated with silk. (Today that would be electrical varnish). In short it would be much too complex to adapt for a classroom demonstration.

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 then 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.

As a side issue, you may also like to know that Oliver Heaviside gave his name to the “Heaviside Layer”, which is the layer of electronic particles which surrounds the earth in the stratosphere and reflects medium frequency radio signals back to earth rather than going in a straight line right off into space and getting lost. **Without the Heaviside Layer most a.m. and f.m. radio signals would not work. Learn something every day, eh?**

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.,

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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 (see Figure 9 above), whereas the non-ferrous metals mentioned above are generally very good conductors of electricity (very low resistance) and do not oxidize very much.

### ◆ Lines of a Magnetic “Field” (or Magnetic Flux)

Obtain two bar magnets. If purchased in a school supply store, they are generally found in pairs, and are about 3” (7.5 cm) long. See Figure 13. If you don’t already have them, simply locate almost any piece of iron or steel rod and cut off two pieces, each about 3” (7.5 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. See Figure 13.



Figure 13:  
The battery is an AA size for scale.

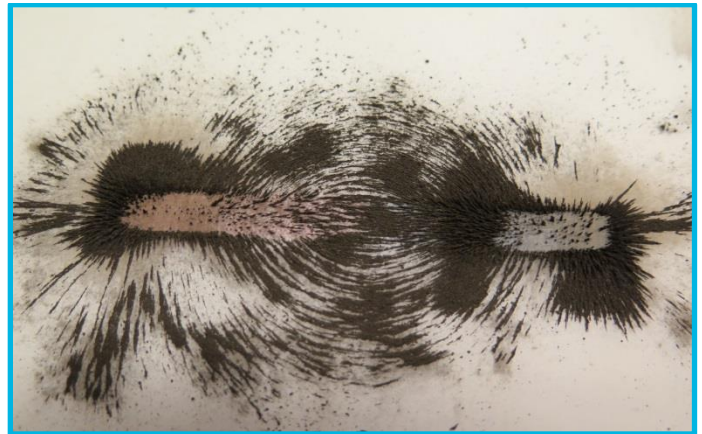


Figure 14:  
One bar magnet (only), under sheet of paper

Unfortunately magnetism cannot be seen, although it can certainly be measured. Figure 14 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 white paper. Sprinkle some iron filings on the paper. You will find that they form a pattern like that in Figure 14, with the filings bunched together at the ends, and curving away in the middle.

You can buy a small jar of iron filings quite cheaply in most school supply stores. Maybe ¼ lbs (100 g) for \$5.00. Alternatively you can make them by hand with a file and a piece of scrap iron, but that is tedious.

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

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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.

Note 3: 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.

Note 4: Keep the magnets away from other small items of electrical equipment such as watches and cellphones in case the magnet disrupts their operation.

### ◆ North and South (Seeking) Poles.

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 or South poles.

### ◆ Magnetic Attraction

If you take both bar-magnets and gradually bring the north pole of one close to the south pole of the other, 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 principal 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.

### ◆ 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. Figure 14 above, illustrates the principal of "Flux Density" very well. The very dark areas at each end represent areas where the magnetic lines are packed very close together (high density) whereas the areas in the middle are less dense. 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.

## ◆ Electromagnets

It was during these experiments by Gauss, Oersted, 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 15 and 16.

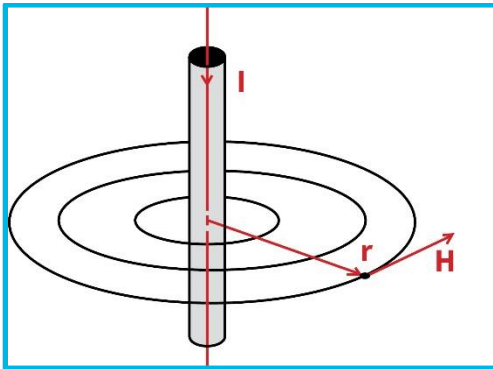


Figure 15:  
Magnetic field formed by a single wire

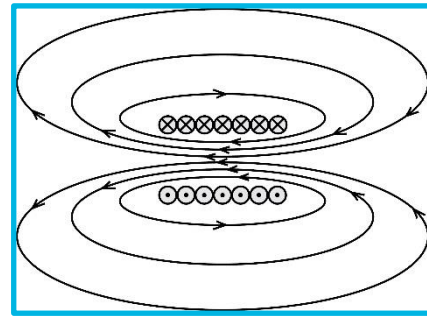


Figure 16:  
Magnetic field formed by a coil of wire.

It was further discovered that this magnetic field could be intensified if the wire was wound up into a cylindrical coil. (See Figure 16 and note the similarity to the flux around a bar magnet shown in Figure 14). 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, which is a useful feature, such as when you may want to pick up something here and put it down over there.

## ◆ 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 strong 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 application) “invisible” to magnetic mines lying beneath the surface. In the case of a research ship, it is important that the sensitive apparatus on the ship is not affected by the earth’s magnetic field.

For those interested, you might like to know that in the early 1800’s, during the change from wooden ships to iron ships, several iron ships were accidentally run aground and lost because the navigator didn’t know how to adjust his magnetic compass properly.

Also, if you dial into the Net and look up “RMS Queen Elizabeth” at the end of World War II (1945) you will find a photo which clearly shows the de-gaussing cable. Learn something every day – yes?

### Basic Electricity and Magnetism

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## ◆ 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 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.

### Visualizing Magnetic Hysteresis:

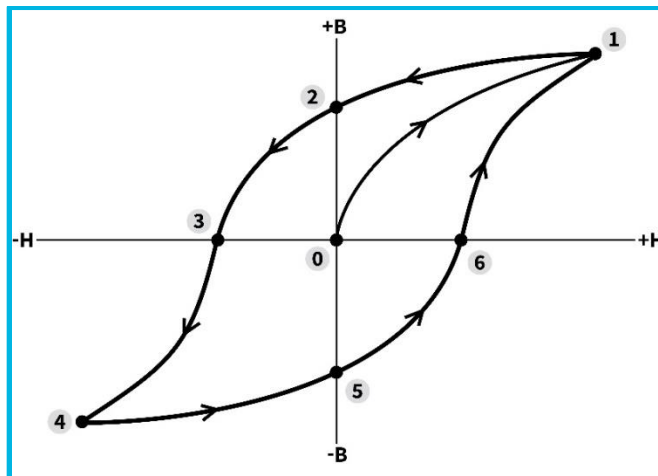


Figure 17:

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 17 and examine it in the following sequence:

1. The horizontal axis represents the force which is producing the magnetization, in this case a coil of wire surrounding a steel core. The international symbol for magnetizing force is  $H$  and is measured in Oersteds after the early Danish experimenter Hans Christian Oersted. The international definition of an Oersted is obscure, but in

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practical terms 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. The vertical axis represents the flux density in the magnetic material. This is measured in lines per square inch of the material, or lines per square cm, as the case may be. The international symbol for magnetic flux density is  $B$ . The international units for flux density are obscure. But think of it as the strength of the magnet. Obtain a series of small steel washers. The stronger the flux the more washers it can lift. Then as you reduce the flux, the washers will begin to drop off.
3. Examine now the central point of the diagram where the two axes intersect. It is intentionally with a zero because at that point there is no current and no magnetic flux. However the first time you attempt to magnetize a new core, you would obtain a curve similar to the line from zero to 1. Point 1 represents the point at which, even though you increase the amperes, you get no more flux. This is known as the saturation point.
4. Then, as you gradually decrease the current in the coil, the flux density would also go down. But surprisingly, even at point 2, when the MMF (Oersteads) is zero, you will find there is still some magnetism left. This is known as the Remanance point.
5. Next you could reverse the connection of the battery and begin gradually increasing the current in the opposite direction. At point 3 on the curve you would reach zero magnetism. The length of the line between zero and 3 represents the Coercion force, because that is the MMF required to "coerce" the magnetic flux in the steel back to zero.
6. Then from point 3 to 4, as you keep increasing the MMF, you will get more magnetic flux until the steel saturates again, but in the opposite direction. So point 4 would be the saturation point in the reverse direction.
7. As a point of interest here, note that in many applications there is no practical difference between a  $+B$  and a  $-B$ . A magnetic crane for example, would lift just as well either way. But in other applications, such as DC and AC motors for example, a reversal of polarity would tend to reverse the rotation of the motor. See other "basic" lessons in this series.
8. From point 4 onwards, it is all downhill, so to speak, because you will find that as you decrease the current again, you will reach a point 5 where there is zero flux density, just as at point 2 previously, and then on to point 6 and back to point 1.
9. Finally, if you were to switch everything off while at points 3 or 6 and then start again, you would find you were in effect at point zero.

**Class Challenge.** Debate item 9 above amongst yourselves. To shut down and then restart, would you be at point zero or either of points 3 or 6?

### ◆ The Practical Meaning of Hysteresis.

You will appreciate that "coercing" the magnetic flux from point 2 down to, 3 or from point 5 down to 6 requires a certain amount of energy. In practical terms what this amounts to is that the area inside the hysteresis curve is an indication of how much energy is consumed in what is practically a net loss to the equipment. And of course in North America this happens 60 times a second. (In other locations this figure is "only" 50 times per second. But it still mounts up. The steel used in electric motors and transformers is therefore specially blended to keep the hysteresis curve as narrow as possible. But in other applications such as electric heating, the hysteresis loss is less important and the hysteresis curve can be much wider.

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Students should note that many other materials also generate internal hysteresis loss and heating. Automobile tires, for example often reach quite high temperatures, even in winter, due to hysteresis in the rubber. If allowed to reach a high temperature, the tire could burst. Remember also that tires are under about 30-40 psi internal pressure.

## ◆ **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**

### **Direct Current 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 electromagnets 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.

### **Alternating Current 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.

## ◆ **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.

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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  $\Omega$ , 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:-

	$\text{Volts} \div \text{Amps} = \text{Ohms}$
Or putting it another way:	$\text{Volts} \div \text{Ohms} = \text{Amps}$
Or again:	$\text{Ohms} \div \text{Amps} = \text{Volts}.$

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

Volts is written as:	V Always upper case
----------------------	---------------------

Current in written text is:	A Always upper case
-----------------------------	---------------------

But current in a mathematical expression is usually written:	I (Some people can be difficult.)
--	-----------------------------------

And Ohms are written as:	Ohm or $\Omega$
--------------------------	-----------------

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!

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## Some Offshoots of Ohm's Law

Power (Rate 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).

Volts = Amps x Ohms, it follows that

Watts = Amps x Amps x Ohms,

Or

Watts = (Amps)<sup>2</sup> 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: Power =  $W = I^2R$

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  $2 \times 2 = 4$ . 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...".

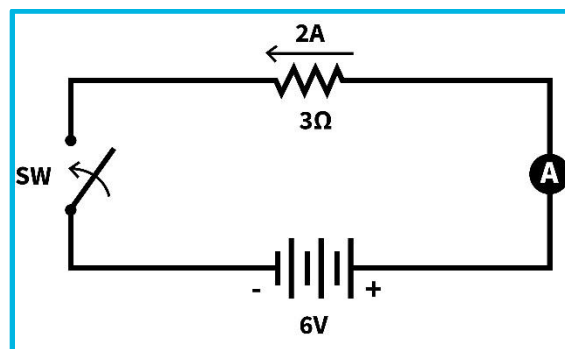


Figure 18

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## Circuits and Symbols

At this stage, it will be useful to look at a few simple circuits and see what they mean. In Figure 18, there are only four components, a 6 V battery, a switch, a resistor of  $3\ \Omega$ , 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 are not rechargeable, and have to be thrown out when discharged.
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.

For simplicity, it is assumed in Figure 18 that there are 3 cells of 2 Volts each, making 6 volts total.

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 around. 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 19, 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  $I.R = 2 \times 2 \times 3 = 12$  Watts

### A Series Circuit

In Figure 19, 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,

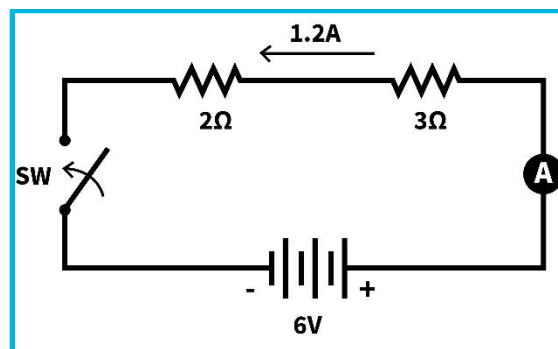


Figure 19

◆ Current is now  $V/R = 6\text{volts} \div 5 \text{ Ohms} = 1.2$  Amps

◆ Power, W will be  $I.R = 1.2 \times 1.2 \times 5 = 7.2$  Watts.

## A Parallel Circuit

In Figure 20 we see two resistors side by side. This will require a little more thought. Look at it this way.

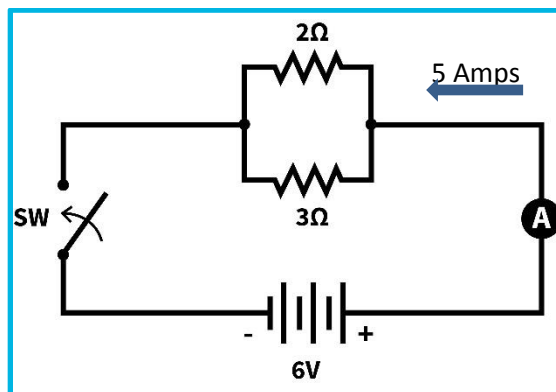


Figure 20

- ◆ The upper resistor has 6 Volts applied to  $2\ \Omega$ . So the current will be  $6 \div 2 = 3$  amps.
- ◆ The lower resistor has 6 Volts applied to  $3\ \Omega$ . So the current will be  $6 \div 3 = 2$  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 Doktor Ohm about that and he would mutter "Volts over Amps = Ohms. Why! That must be  $V/A = 6 \div 5 = 1.2$  Ohms. Yes?"
- ◆ Now here's the clever bit. Supposing we juggled the numbers a little, turned them upside down, and said:  $1 \div 2 = 0.5$ , and  $1 \div 3 = 0.333$ . 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.

## Short-Circuits and the Internal Resistance of a Battery

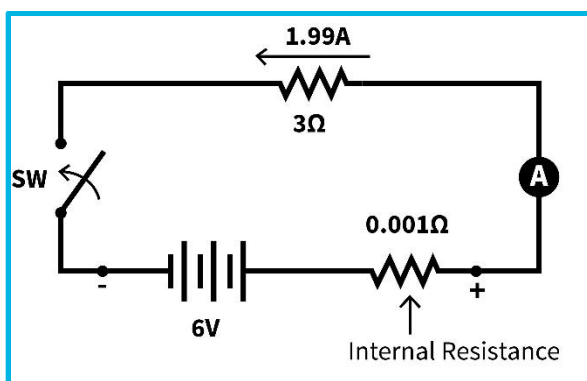


Figure 21

Return for a moment to Figure 20. Let us suppose for a moment that the resistance shown there is not  $3\ \Omega$ , but  $0.3\ \Omega$ . When the switch is closed, the current would be  $6V \div 0.3\ \Omega = 20$  Amps. A big increase. So then let us carry the matter a stage further and assume the

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resistance is only  $0.03\Omega$ . Then the current would, in theory, be  $6 \div 0.03 = 200$  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 21. Note that this is a refined version of Figure 18, 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 above in the Battery section, 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 22. 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

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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?

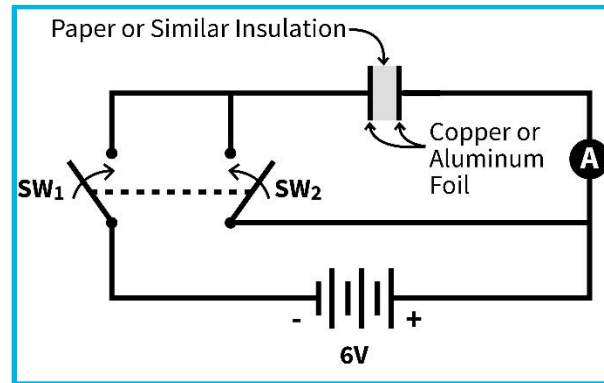


Figure 22

Figure 22 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 22, switches SW<sub>1</sub> and SW<sub>2</sub> 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<sub>1</sub> 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<sub>1</sub> 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.

Then if SW<sub>2</sub> 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

### Basic Electricity and Magnetism

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(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.

### **An interesting side-note.**

The first Trans-Atlantic telegraph (not telephone) cable was laid in 1858. It lasted about 3 weeks. What the operators at that time did not understand was that the cable was in effect a huge capacitor, about 1,650 nautical miles (3,000 km) long. It took 3 minutes to charge up and 3 minutes to discharge, making it difficult to read Morse Code. The first operator tried to speed things up by increasing the applied pressure to several thousand volts – which burned out the electrical insulation and ruined an otherwise good cable. In 1865 Prof. Thompson designed a much better concept which operated at the surprisingly low pressure of only about 10 – 12 Volts, and detected signal currents of only a few micro-amps (millionths of an amp) using an ultra-sensitive mirror galvanometer. In fact all it read was a series of small "twitches" of a rise of current in a positive direction being taken as a dash in Morse code, and a negative twitch as a dot. So in effect the cable was never fully charged at any time. This worked extremely well. Note also that in 1865 the terms "Volt", "Ampere", "Ohm" and "Farad" were unknown. They were literally groping in the dark. Faraday was still alive and was consulted. A subsequent check calculation by the author indicated that the capacitance of both cables was about 400 Farads! Not microfarads, but Farads. But what were the characteristics of Gutta Percha? We don't know for sure.

### **Is there an Application for Electrostatic Electricity?**

It has to be admitted that every-day applications of electrostatic electricity, (as opposed to capacitors) are much fewer than there are for electromagnets. 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 are 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 ( $2 \div 1,000$ , 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  $120V \div 8,000\Omega = 0.015$  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.

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## ◆ 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  $240 \text{ Volts} \div 1,000,000 \text{ ohms} = 0.00024 \text{ amps}$ , 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
Kelvin	A specialized unit of temperature	K (Upper case)
Kilo	Thousand	k (lower case)
milli	1/1,000 or 0.001 or one thousandth	m
micro	1/1,000,000 or one millionth	μ
Electrical Pressure	Voltage	V
Current	Amps	A
Power	Watts	W
Resistance	Ohms	Ω
Insulation	Megohms	M Ω
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  $\mu\text{F}$ , which is, of course one millionth or 0.000001 Farad).

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### **For Teachers:** **Teacher Resources (continued)**

#### ◆ **Hands-On Activities**

1. For a Magnetism hands-on, some iron filings and a bar magnet as shown in Figure.14 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 \$0.50) 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 19, 20 & 21, 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. Demonstrate how a can Capacitor hold a very small amount of energy for a very short period of time? Obtain three LEDs, (\$0.50 each) and a large capacitor. One rated at 10,000  $\mu\text{F}$  and 10- 20 Volts would be suitable (\$5.00). The LEDs are rated at 2.2 V each, so connecting three of 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, taking care to get the polarity right. Just like a battery – positive of the first to the negative of the next, and so on. If you get even one of them wrong, none of them will light up. But once you get them right they will all light up nicely.
7. But as soon as the battery is disconnected, they go out in an instant. Then connect the capacitor to the battery also. (Capacitors do NOT have a polarity problem). The LEDs will flicker briefly as the capacitor "charges up" to 6 V, and then they 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 23 on the next page shows a simple set-up. The above demonstration is extremely inexpensive. The three LEDs cost about \$0.50 each and the capacitor about \$5.00. Total \$6.50. And everything is re-usable.

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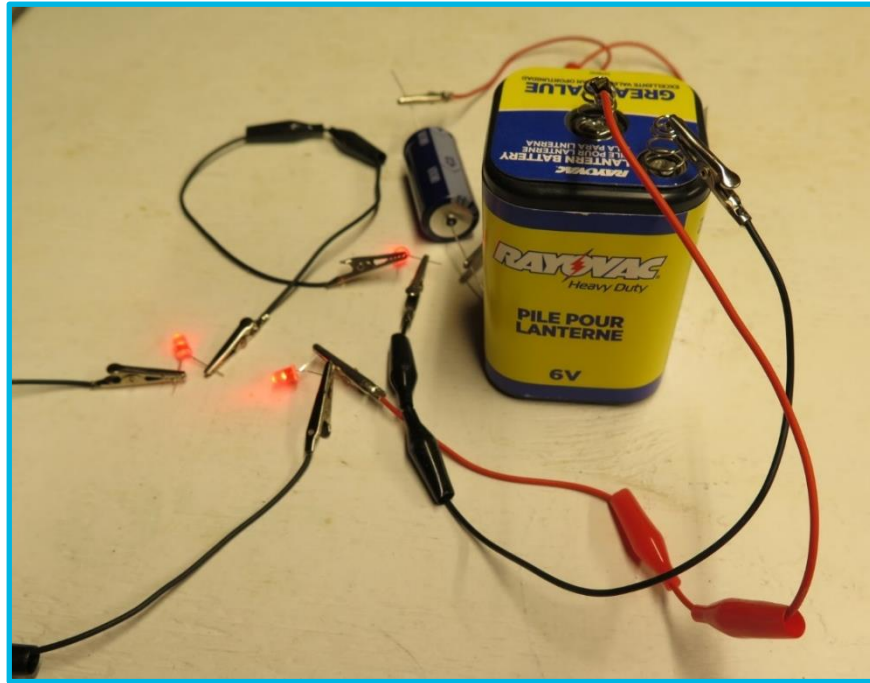


Figure 23

### Warning

LEDs are very delicate. The positive (+) lead is the longer of the two pig-tails. Note that LEDs are DIODES, which means they only pass current in one direction. Each LED is rated at 2.2 Volts. But if you even get just 3 Volts across one, it will be killed instantaneously – literally. LEDs weigh practically nothing so that even the very light and flexible wires used in this demonstration were stiff enough to cause the LEDs to slide about and touch each other, causing a short circuit. In assembling the demonstration above, the author accidentally burned out six. Probably best to tape them down to the table. So don't say you have not been warned!

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## For Students: 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?

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### For Teachers:

#### Alignment to Curriculum Frameworks

**Note:** Lesson plans in this series are aligned to one or more of the following sets of standards:

- U.S. Science Education Standards ([http://www.nap.edu/catalog.php?record\\_id=4962](http://www.nap.edu/catalog.php?record_id=4962))
- U.S. Next Generation Science Standards (<http://www.nextgenscience.org/>)
- International Technology Education Association's Standards for Technological Literacy (<http://www.iteea.org/TAA/PDFs/xstnd.pdf>)
- U.S. National Council of Teachers of Mathematics' Principles and Standards for School Mathematics (<http://www.nctm.org/standards/content.aspx?id=16909>)
- U.S. Common Core State Standards for Mathematics (<http://www.corestandards.org/Math>)
- Computer Science Teachers Association K-12 Computer Science Standards (<http://csta.acm.org/Curriculum/sub/K12Standards.html>)

#### ◆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.

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## For Teachers:

### Alignment to Curriculum Frameworks (continued)

#### ◆ 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.

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