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# Basics of Electricity

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**Abstract:** Electricity is the part and parcel of our modern life and it is the most widely used form of energy. Man has learnt about electricity from nature as it is also a basic part of nature. In the past, many cities and towns were built alongside waterfalls (a primary source of mechanical energy) that turned water wheels to perform work. Before electricity generation began over 100 years ago, houses were lit with kerosene lamps, food was cooled in iceboxes, and rooms were warmed by wood-burning or coal-burning stoves. Beginning with **Benjamin Franklin's** experiment with a kite one stormy night in Philadelphia, the principles of electricity gradually became understood. **Thomas Edison** helped change everyone's life – he perfected his invention – the electric light bulb in 1879. Prior to 1879, direct current (DC) electricity had been used in arc lights for outdoor lighting. In the late-1800s, **Nikola Tesla** pioneered the generation, transmission, and use of alternating current (AC) electricity, which can be transmitted over much greater distances than direct current. Tesla's inventions used electricity to bring indoor lighting to our homes and to power industrial machines. Despite its great importance in our daily lives, most of us rarely stop to think what life would be like without electricity. Yet like air and water, we tend to take electricity for granted. Everyday, we use electricity to do many jobs for us – from lighting and heating/cooling our homes, to powering our televisions and computers. Electricity is a controllable and convenient form of energy used in the applications of heat, light and power. This article discusses about the basics of electricity. It first highlights the fact that electricity exists in nature and then takes an historical perspective to explore the basic mechanisms of producing electricity. The article first explains how static electricity is produced. It then goes on to define an electric current and describe the basic principles of generating electricity from chemical reaction and then finally from the magnetic field employing Faraday's law of electromagnetic induction. Some basic theories underlying electricity are also mentioned alongside with their importance.

## 1. INTRODUCTION

One of the most remarkable and novel discoveries in the last 400 years has been electricity. One may ask, "Has electricity been around that long?" The answer is yes, and perhaps much longer. But the practical use of electricity has only been at our disposal since the mid-to late 1800s, and in a limited way at first. At the world exposition in Paris in 1900, for example, one of the main attractions was an electrically lit bridge over the river Seine.

Long before any knowledge of electromagnetism existed, people were indirectly aware of the effects of electricity. Lightning, of course, and certain other manifestations of electricity, were known to the philosophers of ancient times, but to them no thought was more remote than that these manifestations had a common origin. Ancient Egyptians were aware of shocks when interacting with **electric fish**

(such as the *Malapterurus electricus*) or other animals (such as **electric eels**). The shocks from animals were apparent to observers since pre-history by a variety of peoples that came into contact with them. Texts from **2750 BC** by the ancient Egyptians, referred to these fish as "**thunderer of the Nile**", and saw them as the "**protectors**" of all the other fish. Several ancient writers, such as **Pliny the Elder** and **Scribonius Largus**, attested to the numbing effect of **electric shocks** delivered by **catfish** and **torpedo rays**.

Possibly the earliest and nearest approach to the discovery of the identity of lightning, and electricity from any other source, is to be attributed to the **Arabs**, who **before the 15th century** had the Arabic word for lightning (**raad**) applied to the **Electric ray**.

According to **Thales of Miletus**, writing at around **600 BC**, noted that a **form of electricity** was observed by the **Ancient Greeks** that would cause a particular **attraction** by rubbing fur on various substances, such as **amber**, for which the Greek word is **electron**. Thales wrote on the effect now known as **static electricity**. **The electrostatic phenomena was again reported millennia later by Roman and Arabic naturalists and physicians.**

A number of objects found in **Iraq** in 1938 **dated to the early centuries AD** (**Sassanid Mesopotamia**), called the **Baghdad Battery**, resembles a **voltaic** or **galvanic cell** and is believed by some to have been used for **electroplating**.

## **2. STATIC ELECTRICITY**

The knowledge of **static electricity** dates back to the earliest civilizations, but for millennia it remained merely an interesting and mystifying phenomenon, without a theory to explain its behavior and often confused with magnetism. The ancients were acquainted with other curious properties possessed by **two minerals, amber** and **magnetic iron ore**. The former, when rubbed, attracts light bodies : the latter has the power of attracting iron.

Electricity has been moving in the world forever. Lightning is a form of electricity. It is electrons moving from one cloud to another or jumping from a cloud to the ground. Have you ever felt a shock when you touched an object after walking across a carpet? A stream of electrons jumped to you from that object. This is called **static electricity**.

### **2.1 Experiments Conducted on Static Electricity**

The natural phenomenon of static electricity was known at least as early as the 6th century BC, as attested by **Thales of Miletus**. The earliest method of generating electricity occurred by creating a static charge. In **1660**, Otto von Guericke constructed the **first electrical machine** that *consisted of a large sulphur globe which, when rubbed and turned, attracted feathers and small pieces of paper.* Guericke was **able to prove that the sparks generated were truly electrical**. Scientific research into the subject began when machines were built to create it artificially, such as the friction generator developed by **Otto von Guericke**.

By the end of the 17th Century, researchers had developed practical means of generating electricity by friction in **electrostatic generator**, but the development

of electrostatic machines did not begin in earnest until the 18th century, when they **became fundamental instruments** in the studies about the new science of **electricity**. Electrostatic generators operate by using manual (or other) power to transform **mechanical work** into **electric energy**. They develop **electrostatic charges** of opposite signs rendered to two conductors, using only electric forces.

In **1741**, **Ellicott** *"proposed to measure the strength of electrification by its power to raise a weight in one scale of a balance while the other was held over the electrified body and pulled to it by its attractive power"*.

The **Sir William Watson** already mentioned conducted numerous experiments, about **1749**, to ascertain **the velocity of electricity in a wire**, which experiments, although *perhaps not so intended, also demonstrated the possibility of transmitting signals to a distance by electricity*. In these experiments an insulated wire 12,276 feet in length was employed and the transmission of a signal from one end of the wire to the other appeared to the observers to be instantaneous. **Monnier** in France had previously made somewhat similar experiments, sending shocks through an iron wire 1,319 feet long.

The **Leyden jar**, a type of **capacitor** for electrical energy in large quantities, was invented at **Leiden University** by **Pieter van Musschenbroek** in **1745**. **William Watson**, when experimenting with the Leyden jar, discovered in **1747** that *a discharge of static electricity was equivalent to an **electric current***.

*The capacitive property, now and for many years availed of in the electric condenser, was first observed by Von Kleist of Leyden in **1754**. **Von Kleist** happened to hold, **near his electric machine, a small bottle, in the neck of which there was an iron nail**. Touching the iron nail accidentally with his other hand he received a severe electric shock. In much the same way Prof. Pieter van Musschenbroeck assisted by Cunaens received a more severe shock from a somewhat similar glass bottle. Sir William Watson of England greatly improved this device, by covering the bottle, or jar, outside and in with tinfoil. **This piece of electrical apparatus will be easily recognized as the well-known Leyden jar, so called by the Abbot Nollet of Paris, after the place of its discovery.***

## **2.2 Experiments on Static Electricity by Maxwell**

Let us now concentrate on the discussion of the fundamental concepts involved in the state of electrification of a body. The scheme of James Clerk Maxwell in his book, **"A Treatise on Electricity and Magnetism"** describes a set of basic experiments conducted on static electricity. describe a set of basic experiments:

Let us first take two pieces of glass and two pieces of resin. We note that none of them attract or repel one another. We now rub one piece of glass with one piece of resin together but do not separate them. These two unseparated glass-resin pieces neither attract nor repel the other pieces of glass or resin. We then rub the second set of glass and resin together. Now separate both sets of glass-resin combination and suspend with white silk threads. We observe the following:

- (a) Two pieces of glass repel each other.
- (b) Two pieces of resin repel each other.
- (c) A piece of glass attracts a piece of resin and vice-versa.

The phenomena of attraction and repulsion associated with the rubbing of glass and resin are termed electrical phenomena and the glass and the resin exhibiting such property are said to be in states of electrification. From this experiment we conclude that the piece of glass exhibits one kind of electrification and the piece of resin another kind.

Many substances other than glass and resin exhibit the phenomena of electrification. We classify those substances which when electrified repel electrified glass and attract electrified resin under **glass group** and substances having opposite property namely when electrified attract glass and repel resin under **resin group**. The glass group when electrified is said to be **vitreously or positively electrified** and the resin group **resinously or negatively electrified**. The term ‘positive’ and ‘negative’ are, of course, arbitrary.

We refer to the process of electrification by rubbing as **electrification by friction**.

Sir James Jeans, in his book “**The Mathematical Theory of Electricity and Magnetism**”, has given a list of important substances of the above type. We reproduce the list in Table I below.

**Table I:** Substances that produce Static Electricity by Friction.

Name of Substance	The Rule
Cat's skin	If any two substances from this list are rubbed then the substance appearing first in the list will be positively charged and the other negatively charged.
Glass	
Ivory	
Silk	
Rock Crystal	We say that the first substance is electropositive with respect to the other.
The Hand	
Wood	
Sulphur	
Flannel	
Cotton	
Shellac	
Caoutchouc	
Resins	
Guttapercha	
Metals	
Guncotton	

There are also several methods of electrification other than the frictional method.

The method of electrifying a metal body by bringing an electrified object in its vicinity is called **electrification by induction**.

When charge is transferred from a charged body (say a charged metal jar) through a conductor (metal wire) to another metal object, this method of electrifying the metal object as **electrification by conduction**.

If instead of the metal wire, a rod of glass, resin, guttapercha or white silk thread was used to connect the metal jar and the metal object in the process of electrification by conduction, the metal object would not have been electrified indicating that the transfer of electricity cannot take place through such materials. These substances are referred to as **Nonconductors** of electricity and also as **Insulators**. Thus material objects can be classified broadly as conductors and insulators. This classification was probably first introduced by Stephen Gray (1696–1736).

It must be pointed out that the difference between conductors and insulators is one of degree only. Some materials are better conductors than others and some materials are better insulators than others. There is a whole range of materials possessing conducting property from a small value to a high value. There is, of course, no such thing as a perfect conductor or a perfect insulator in nature. More logical and realistic terms should be good conductors and bad conductors.

The results of Maxwell's other experiments can be summarized as follows.

- “If we rub two bodies, which are initially uncharged, equal and opposite charges are generated on the two bodies, the total quantity of charges being algebraically zero.”
- Bodies with like charges repel and those with opposite charges attract.
- Also, a charged body attracts a neutral body.
- The electrification of a body is a physical quantity that can be measured.
- Several quantities of charges can be added algebraically to obtain a net amount of charge. We can then speak of an electrical body to be charged with a “certain quantity of positive or negative electricity”.
- Electricity can neither be created nor destroyed just like any other physical material and that if a quantity of electricity within a closed surface is increased or diminished, the difference of charges must have gone in or out of the closed surface.

### 2.3 Use of Static Electricity

The ancients held some concept that **shocks could travel along conducting objects**. Patients suffering from ailments such as **gout** or **headache** were directed to touch **electric fish** in the hope that *the powerful jolt might cure them*.

About **1750** various **tests were made** by different experimenters to ascertain **the physiological and therapeutical effects of electricity**. Mainbray (or Mowbray) in Edinburgh examined *the effects of electricity upon plants and concluded that the growth of two myrtle trees was quickened by electrification. These myrtles were electrified "during the whole month of October, 1746, and they put forth branches and blossoms sooner than other shrubs of the same kind not electrified."*

*The Abbé Menon tried the effects of a continued application of electricity upon men and birds and found that the subjects experimented on lost weight, thus apparently showing that electricity quickened the excretions. The efficacy of electric shocks in cases of paralysis was tested in the county hospital at Shrewsbury, England, with rather poor success. In one case reported a palsied arm was somewhat improved, but*

the dread of the shocks became so great that the patient preferred to forego a possible cure rather than undergo further treatment. In another case of partial paralysis the electric treatment was followed by temporary total paralysis. A second application of this treatment was again followed by total paralysis, whereupon ***the further use of electricity in this case was stopped***. For further accounts of ***the early use of electricity as a remedial agent*** the reader may consult De la Rive's 'Electricity.'

The first suggested use of static electricity was the so-called “**electric pistol**”. Invented by Alessandro Volta (1745-1827), an electrical wire was placed in a jar filled with methane gas. By sending an electrical spark through the wire, the jar would explode. Volta then ***thought of using this invention to provide long distance communications***, albeit only addressing one Boolean bit. An iron wire supported by wooden poles was to be strung from Como to Milan, Italy. At the receiving end, the wire would terminate in a jar filled with methane gas. On command, an electrical spark is sent by wire that would detonate the electric pistol to signal a coded event. ***This communications link was never built***.

With the discovery, by the experiments of Watson and others, *that electricity could be transmitted to a distance*, the idea of making practical use of this phenomenon began, about **1753**, to engross the minds of "inquisitive" persons, and to this end suggestions looking to the employment of electricity in the transmission of intelligence were made. The first of the methods devised for this purpose was probably that, due to **Besage (1774)**. This method consisted in the employment of 24 wires, insulated from one another and each of which had a pith ball connected to its distant end. Each wire represented a letter of the alphabet. To send a message, a desired wire was charged momentarily with electricity from an electric machine, whereupon the pith ball connected to that wire would fly out; and in this way messages were transmitted. Other methods of telegraphing in which frictional electricity was employed were also tried.

## **2.4 Early Theories on Electricity**

*Theories regarding the nature of electricity were not clear at the early stages of the discovery of electricity until the discovery of electron only in 1897 by H J Thomson. At this period the existing theories were quite vague and those prevalent were more or less conflicting.*

**One-Fluid Theory:** This theory appears to have been proposed by Benjamin Franklin (1751). He suggested that uncharged bodies contain an indestructible ‘electric-fluid’. When a body contains this fluid to a normal level, no electric effects are observable. A positively charged body is supposed to have an excess fluid content and a negatively charged body a deficiency in the electric-fluid content with respect to the normal amount. If a conductor between a positively charged body and a negatively charged body, the excess amount of fluid flows from the positive to the negative body. The net charge on the system is then equal to the algebraic sum of the two amounts of charges. Franklin supposed furthermore that the particles of the electric-fluid repelled each other but attracted the particles of ordinary matter.

If two bodies are rubbed, electric fluid is simply transferred from one body to another. In the normal state, the quantities of ordinary matter and electric-fluid are

equal so that there is neither attraction nor repulsion between the bodies in the normal state. Electricity can neither be created nor destroyed so that the total quantity of electricity is always conserved. It can flow only through conductors but not through insulators.

Benjamin Franklin considered that electricity was an imponderable fluid pervading everything, and which, in its normal condition, was uniformly distributed in all substances. *He assumed that the electrical manifestations obtained by rubbing glass were due to the production of an excess of the electric fluid in that substance and that the manifestations produced by rubbing wax were due to a deficit of the fluid.* This theory was opposed by the **"two-fluid" theory** due to **Robert Symmer** proposed in **1759**.

**Two-Fluid Theory:** In 1732, C. F. du Fay began to conduct several experiments. In his first experiment, Du Fay concluded that all objects except metals, animals, and liquids could be electrified by rubbing and that metals, animals and liquids could be electrified by means of an electric machine. In 1737 Du Fay and Hawksbee independently discovered what they believed to be two kinds of frictional electricity; one generated from rubbing glass, the other from rubbing resin. From this, Du Fay theorized that electricity consists of two electrical fluids, "*vitreous*" and "*resinous*", that are separated by friction and that neutralize each other when combined.

The two-fluid theory that was proposed by **Robert Symmer** in **1759**, considers the ***vitreous*** and ***resinous*** electricity were regarded as imponderable fluids, each fluid being composed of mutually repellent particles while the particles of the opposite electricity are mutually attractive. When the two fluids unite by reason of their attraction for one another, their effect upon external objects is neutralized. The act of rubbing a body decomposes the fluids one of which remains in excess on the body and manifests itself as vitreous or resinous electricity. This two-fluid theory would later give rise to the concept of *positive* and *negative* electrical charges devised by Benjamin Franklin.

The Greeks noted that the **amber** buttons could attract light objects such as **hair** and that if they rubbed the amber for long enough they could even get a **spark** to jump. During this time in **alchemy** and **natural philosophy**, the existence of a medium of the ***æther***, a space-filling substance or field, thought to exist.

However, another pioneer was **Robert Boyle**, who in **1675** stated that ***electric attraction and repulsion can act across a vacuum***. One of his important discoveries was that electrified bodies in a vacuum would attract light substances, this indicating that the electrical effect did not depend upon the air as a medium. He also added resin to the then known list of electrics.

About **1784** C. A. **Coulomb**, after whom is named the electrical unit of quantity, devised the **torsion balance**, by means of which he discovered what is known as Coulomb's law; — ***The force exerted between two small electrified bodies varies inversely as the square of the distance***; not as **Aepinus** in his theory of electricity had assumed, merely inversely as the distance. According to the theory advanced by Cavendish "the particles attract and are attracted inversely as some less power of the distance than the cube."

## 2.5 Causes of Static Electricity

Static electricity refers to the accumulation of excess electric charge in a region with poor electrical conductivity (an insulator), such that the charge accumulation persists. The effects of static electricity are familiar to most people because we can see, feel and even hear the spark as the excess charge is neutralized when brought close to a large electrical conductor (for example a path to ground), or a region with an excess charge of the opposite polarity (positive or negative).

The materials we observe and interact with from day-to-day are formed from **atoms** and **molecules** that are electrically neutral, having an equal number of positive charges (**protons**, in the **nucleus**) and negative charges (**electrons**, in **shells** surrounding the nucleus). The phenomenon of static electricity requires a sustained separation of positive and negative charges.

### 2.5.1 Contact induced charge separation

*Triboelectric effect:* Electrons can be exchanged between materials on contact; materials with weakly bound electrons tend to lose them, while materials with sparsely filled outer shells tend to gain them. This is known as the triboelectric effect and results in one material becoming positively charged and the other negatively charged. The polarity and strength of the charge on a material once they are separated depends on their relative positions in the triboelectric series. The triboelectric effect is the main cause of static electricity as observed in everyday life, and in common high-school science demonstrations involving rubbing different materials together (e.g. fur and an acrylic rod) and it causes your hair to stand up.

### 2.5.2 Pressure induced charge separation

*Piezoelectric effect:* Certain types of crystals and ceramics generate a separation of charge in response to applied mechanical stress.

### 2.5.3 Heat induced charge separation

*Pyroelectric effect:* Certain materials generate a separation of charge in response to heating. All pyroelectric materials are also piezoelectric, the two properties being closely related.

### 2.5.4 Charge induced charge separation

*Electrostatic induction:* A charged object brought into the vicinity of an electrically neutral object will cause a separation of charge within the conductor as charges of the same polarity are repelled and charges of the opposite polarity are attracted. As the force due to the interaction of electric charges falls off rapidly with increasing distance, the effect of the closer (opposite polarity) charges is greater and the two objects feel a force of attraction. The effect is most pronounced when the neutral object is an electrical conductor as the charges are more free to move around.

Careful grounding of part of an object with a charge induced charge separation can permanently add or remove electrons, leaving the object with a global, permanent

charge. This process is integral to the workings of the **Van de Graaf Generator**, a device **commonly used to demonstrate the effects of static electricity**.

*Static discharge:* The spark associated with static electricity is caused by electrostatic discharge, or simply static discharge, as excess charge is neutralized by a flow of charges from or to the surroundings. In general, significant charge accumulations can only persist in regions of low electrical conductivity (very few charges free to move in the surroundings), hence the flow of neutralizing charges often results from neutral atoms and molecules in the air being torn apart to form separate positive and negative charges which then travel in opposite directions as an electric current, neutralizing the original accumulation of charge. Air typically breaks down in this way at around 30,000 volts-per-centimeter depending on humidity. The discharge superheats the surrounding air causing the bright flash, and produces a shockwave causing the clicking sound.

The feeling of a static electric shock is caused by the stimulation of nerves as the neutralizing current flows through the human body. Due to the ubiquitous presence of water in places inhabited by people, the accumulated charge is generally not enough to cause a dangerously high current.

Lightning is a dramatic natural example of static discharge. While the details are unclear and remain the subject of debate, the initial charge separation is thought to be associated with contact between ice particles within storm clouds. Whatever the cause may be, the resulting lightning bolt is simply a scaled up version of the sparks seen in more domestic occurrences of static discharge. The flash occurs because the air in the discharge channel is heated to such a high temperature that it emits light by **incandescence**. The clap of **thunder** is the result of the shockwave created as the superheated air rapidly expands.

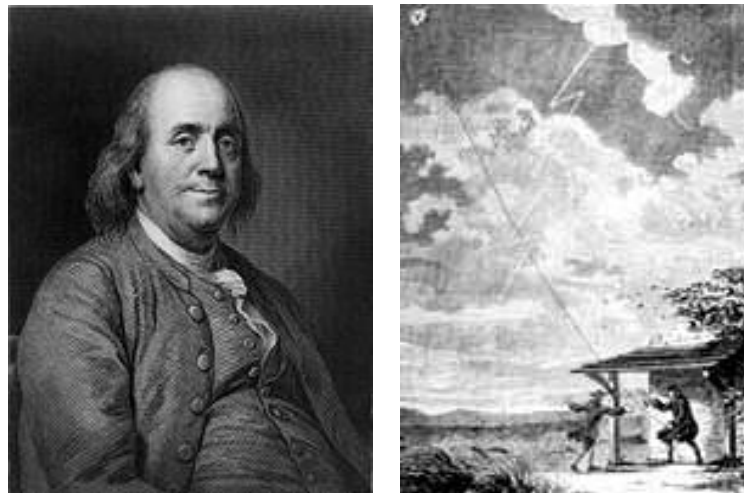


**Figure 1:** Lightning – the natural static discharge.

Lightning is a dramatic natural example of static discharge. While the details are unclear and remain the subject of debate, the initial charge separation is thought to be associated with contact between ice particles within storm clouds. Whatever the cause may be, the resulting lightning bolt is simply a scaled up version of the sparks seen in more domestic occurrences of static discharge. The flash occurs because the air in the discharge channel is heated to such a high temperature that it emits light by **incandescence**. The clap of **thunder** is the result of the shockwave created as the superheated air rapidly expands.

## 2.6 Lightning and Electricity are the Same

For thousands of years, people all over the world have been fascinated by lightning. Some people must have wondered how to put that kind of power to practical use. But it was not until the 18th century that the path to the everyday use of electrical power began to take shape. The connection between static electricity and storm clouds was famously demonstrated by **Benjamin Franklin** in **1752**. To prove that lightning was electrical, he flew a kite during a thunderstorm. He tied a metal key onto the string and, as he suspected it would, electricity from the storm clouds flowed down the string, which was wet, and he received an electrical shock. Franklin was extremely lucky not to have been seriously hurt during this **experiment**, but he was excited to have proved his idea.



**Figure 2:** Benjamin Franklin and his Kite experiment.  
(He proved that lightning was a form of electricity).

Up to the time of Franklin's historic kite experiment, the identity of the **electricity developed by rubbing and by electric machines (frictional electricity)**, with lightning had not been generally established. **Dr. Wall, Abbot Nollet, Hawkesbee, Gray and Winckler** had indeed suggested the resemblance between the phenomena of "electricity" and "lightning," Gray having intimated that they only differed in degree. It was doubtless **Franklin**, however, who first proposed tests to determine the sameness of the phenomena. In a letter **to Peter Comlinson**, London, **19 Oct. 1752**. Franklin, referring to his kite experiment, wrote, *"At this key the phial (Leyden jar) may be charged; and from the electric fire thus obtained spirits may be kindled, and all the other electric experiments be formed which are usually done by the help of a rubbed glass globe or tube, and thereby the sameness of the electric matter with that of lightning be completely demonstrated."*

**Dalibard**, at **Marley**, near Paris, on **10 May 1742**, by means of a **vertical iron rod 40 feet long**, obtained results corresponding to those recorded by **Franklin and somewhat prior to the date of Franklin's experiment**. Franklin's important demonstration of the sameness of frictional electricity and lightning doubtless added zest to the efforts of the many experimenters in this field in the last half of the 18th century, to advance the progress of the science.

Franklin's observations aided later scientists such as **Michael Faraday, Luigi Galvani, Alessandro Volta, André-Marie Ampère**, and **Georg Simon Ohm**

whose work provided the basis for modern electrical technology. The work of Faraday, Volta, Ampere, and Ohm is honored by society, in that fundamental units of electrical measurement are named after them.

### **2.7 Modern Viewpoint of Electricity**

It should be noted here that electron was discovered much later in **1897** by **H J Thomson**. During the entire period of electricity generated from voltaic cells and electromagnetic generators, before 1897, people thought that some electric fluid or electric fire that flows through the circuit produces electrical current. However, the modern viewpoint of electricity is that the flow of electrons in a conductor produces the electricity. The modern viewpoint of electricity will be elaborated in section 4.

## **3. CURRENT ELECTRICITY OR ELECTRICAL CURRENT**

The ancients held some concept that electric ***shocks could travel along conducting objects***. Later, flow of electricity was discovered first from the chemical reaction and then much later from magnetic field. These two forms of electricity may be referred to as current electricity or electrical current.

In **1822** Sweiprger devised the first **galvanometer**. This instrument was subsequently much improved by **Wilhelm Weber (1833)**.

In **1825 William Sturgeon** of Woolwich, England, invented the **horseshoe** and **straight bar electromagnet**, receiving therefore the silver medal of the Society of Arts.

In **1827 George Simon Ohm** announced the now famous Ohm's law that bears his name, that is: Electromotive force = Current  $\times$  Resistance or

$$V = R \times I \dots \dots (1)$$

In **1837 Gauss** and **Weber** (both noted workers of this period) jointly invented a *reflecting galvanometer* for **telegraph purposes**. This was the forerunner of the Thomson reflecting and other exceedingly sensitive galvanometers once used in submarine signaling and still widely employed in electrical measurements.

### **3. 1 Voltaic Electricity**

The first mention of voltaic electricity, although not recognized as such at the time, was probably made by **Sulzer in 1767**, ***who on placing a small disc of zinc under his tongue and a small disc of copper over it, observed a peculiar taste when the respective metals touched at their edges. Sulzer assumed that when the metals came together they were set into vibration, this acting upon the nerves of the tongue, producing the effects noticed.***

Prof. Luigi Galvani is famous for his experiments concerning "the electrical forces in muscular movements", leading up to his theory of **animal electricity**. This began with the accidental observation, in 1780, while conducting experiments at Bologna University, on one occasion, his attention had been turned to by the ***twitching of a frog's legs in the presence of an electric machine***. He also observed that *the*

*muscles of a frog which was suspended on an iron balustrade by a copper hook that passed through its dorsal column underwent lively convulsions without any extraneous cause; the **electric machine being at this time absent**. The legs of a dissected frog twitched (muscles underwent contraction) when the bared crural nerve was touched with the steel scalpel. He worked diligently along these lines for next 11 years. His theory discovered that **when nerve and muscle touch two dissimilar metals in contact with each other, a contraction of the muscle takes place**. But he incorrectly thought that the fluid in the frog's body was the source of the electricity. Thus he termed this phenomenon as animal electricity. To account for this phenomenon Galvani assumed that electricity of opposite kinds existed in the nerves and muscles of the frog; **the muscles and nerves constituting the charged coatings of a Leyden jar**. Galvani published the results of his discoveries, together with his ingenious and simple theory, in **1791**, which at once engrossed the attention of the physicists of that time; the most prominent of whom was, **Alessandro Volta**, a professor of physics at Pavia.*

Galvani's theory of animal electricity has been abandoned by scientists on account of later discoveries by Italian inventor Alessandro Volta. Volta proved that the source of the electricity was a reaction caused by the animal's body fluids being touched by two different types of metal, copper and iron, acting as "electromotors," and that *the muscles of the frog played the part of a conductor, completing the circuit*.

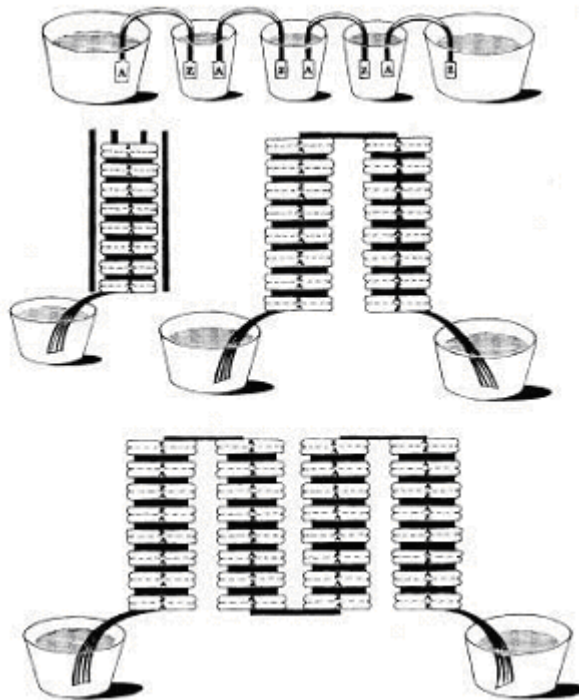
### **3.1.1 Volta's Discovery of Electrochemical Cell**

Beginning his work in 1794, Volta observed the electrical interaction between two different metals submerged near each other in an acidic solution. Based on this principle, his first battery consisted of a series of alternating copper and zinc rings in an acid solution known as an electrolyte. His device for generating a consistent flow of electricity was invented in 1800. He called his invention a column battery, although it came to be commonly known as the Volta battery, Voltaic cell or Voltaic pile. In the same year, Volta released his discovery of a continuous source of electricity to the Royal Society of London.



**Figure 3:** Alessandro Volta – the Italian physicist and his voltaic pile.

Volta discovered further that the voltage would increase when voltaic cells were stacked on top of each other.



**Figure 4:** Four variations of Volta's electric battery.

(Silver and zinc disks are separated with moist paper. Courtesy: ©Cadex Electronics Inc.)

France was one of the first nations to officially recognize Volta's discoveries. At the time, France was approaching the height of scientific advancements and new ideas were welcomed with open arms to support the political agenda. By invitation, in 1801, Volta addressed the Institute of France in a series of lectures at which Napoleon Bonaparte was present as a member of the Institute (who later ennobled him, Count, for his discoveries).

### 3.1.2 How batteries work

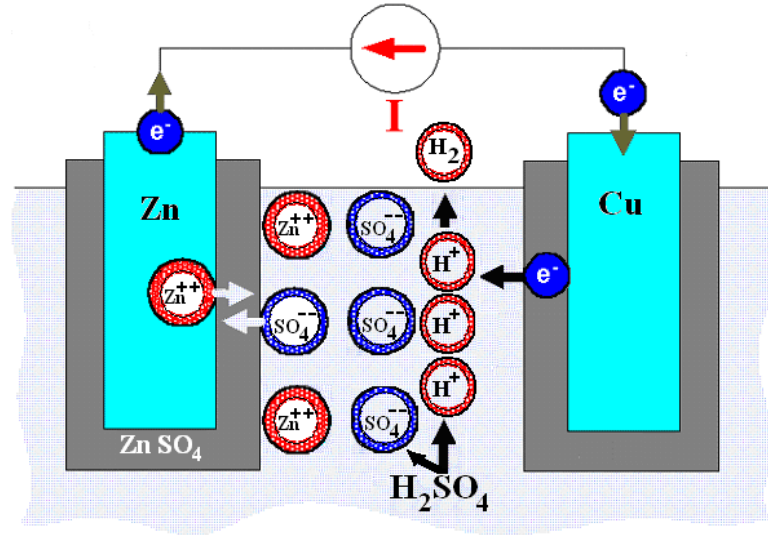
A battery produces electricity using two different metals in a chemical solution. A chemical reaction between the metals and the chemicals frees more electrons in one metal than in the other. One end of the battery is attached to one of the metals; the other end is attached to the other metal. The end that frees more electrons develops a positive charge and the other end develops a negative charge. If a wire is attached from one end of the battery to the other, electrons flow through the wire to balance the electrical charge. When a metal is immersed in a solution, such as a water solution of sulfuric acid, the metal tends to lose electrons. Each metal has a greater or lesser tendency to lose electrons compared to other metals. For example, imagine that a strip of copper metal and a strip of zinc metal are both immersed in a solution of sulfuric acid. In this case, the **copper** metal has a greater tendency to lose electrons than does the **zinc** metal.

Voltaic cells contain three main components: two different metals, a solution into which the two metals are immersed, and an external circuit (such as a wire) that connects the two metals to each other.

- **Anode:** The electrode in an electrochemical cell at which electrons are given up to a reaction.

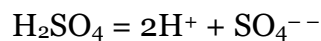
- **Cathode:** The electrode in an electrochemical cell at which electrons are taken up from a reaction.
- **Electrode:** A material that will conduct an electrical current, usually a metal, used to carry electrons into or out of an electrochemical cell.

A voltaic cell may be shown in Figure 5 for demonstration purposes. In this example the two half-cells are submersed in water solution of sulfuric acid ( $\text{H}_2\text{SO}_4$ ).

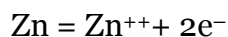


**Figure 5:** Chemical reactions in the electrolyte causes flow of electron outside the circuit.

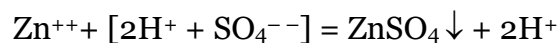
Upon dissolving in water the  $\text{H}_2\text{SO}_4$  molecule becomes  $2\text{H}^+$  ions and  $\text{SO}_4^{--}$  ions as follows.



The first reaction involves the oxidation of Zinc atoms on the electrode surface to  $\text{Zn}^+$  ions in solution at the interface.

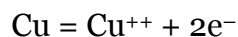


The second reaction occurs immediately after the formation of  $\text{Zn}^+$  ions.

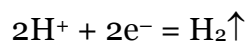


These ions combine with  $\text{SO}_4^{--}$  ions, already in solution, to form the ionic compound  $\text{ZnSO}_4$ .

The other electrode Copper also involves the oxidation of Cu atoms on the electrode surface as follows.

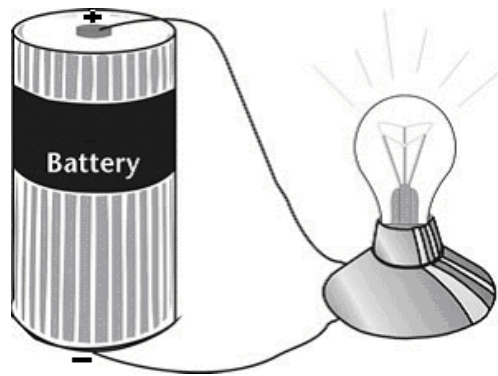


Finally, the released electrons from Copper electrode combine with the  $2\text{H}^+$  ions to make Hydrogen atom and leaves the solution from the top.



Thus Zn accumulates more electron and becomes negative (Cathode) and as Cu loses more electron it becomes more positive (Anode).

The reaction continues like this. However, if the two plates are now externally connected by a wire or any **load**, the electrons flow from Zn plate to Cu plate to balance the electrons in the Cu plate. This is how a flow of electron would persist. The direction of flow of electric current is said to persist from the positive plate to the negative plate (opposite to the direction of flow of electrons). A **load** is a device that does work or performs a job. If a load – such as a light bulb – is placed along the wire, the electricity can do work as it flows through the wire.



**Figure 6:** Load connected to a dry-cell dc battery.

Here, electrons flow from the negative end of the battery through the wire to the light bulb and then through the upper wire back to the positive end of the battery. Electricity travels in closed loops, or circuits (from the word circle). It must have a complete path before the electrons can move. If a circuit is open, the electrons cannot flow. When we flip on a light switch, we close a circuit. The electricity flows from the electric wire through the light bulb and back into the wire. When we flip the switch off, we open the circuit. No electricity flows to the light bulb.

In **1802**, **Dr. William Cruickshank** designed the first electric battery capable of mass production. Cruickshank had arranged square sheets of copper, which he soldered at their ends, together with sheets of zinc of equal size. These sheets were placed into a long rectangular wooden box that was sealed with cement. Grooves in the box held the metal plates in position. The box was then filled with an electrolyte of brine, or watered down acid. Before the introduction of dynamo electric machines, voltaic or primary batteries were extensively used for electro-plating and in telegraphy.

A battery converts chemical energy directly to electrical energy. It consists of one or more voltaic cells. Each voltaic cell consists of two **half cells** connected in series by a conductive electrolyte. One half-cell is the negative electrode (the **cathode**) and the other is the positive electrode (the **anode**). The electrical potential difference, or across the terminals of a battery is known as **terminal voltage** and is measured in **volts**. The terminal voltage of a battery that is neither charging nor discharging is called the **open-circuit voltage** and equals the e.m.f. of the battery. Because of internal resistance, the terminal voltage of a battery that is discharging is smaller in magnitude than the open-circuit voltage and the terminal voltage of a battery that is charging exceeds the open-circuit voltage. An ideal battery has negligible internal resistance, so it would maintain a constant terminal voltage of until exhausted, then dropping to zero.

### 3.1.3 Primary and Secondary Batteries

*Primary batteries are ready to produce current as soon as they are assembled.* Disposable batteries, also called primary cells, are intended *to be used once and discarded*. Primary cells cannot be reliably recharged, since the chemical reactions are not easily reversible and active materials may not return to their original forms. Battery manufacturers recommend against attempting to recharge primary cells. In **1836**, **John F. Daniell**, an English chemist, developed an improved battery which produced a steadier current than Volta's device. Until then, all batteries had been composed of primary cells, meaning that they could not be recharged.

Most types of *secondary batteries* must be *charged before use*; they are usually assembled with active materials in the discharged state. A very few types are manufactured in the charged state. For example: the Lithium type batteries are manufactured fully charged. When discharged, rechargeable batteries or **secondary cells** can be recharged by applying electrical current, which reverses the **chemical reactions** that occur during its discharge. Devices to supply the appropriate current are called chargers or rechargers. In **1859**, the French physician **Gaston Platé** invented the first rechargeable battery. This secondary battery was based on lead acid chemistry, a system that is still used today.

## 3.2 Electricity from Magnetic Field

The third method of generating electricity was discovered relatively late — electricity through magnetism.

### 3.2.1 Magnets and its Properties

Magnet was discovered in Magnesia in asia minor. **Magnesia** (**Greek**: Μαγνησία, *Magnisía*, deriving from the tribe name **Magnetes**, is the name of the southeastern area of **Thessaly** in central **Greece**. The modern prefecture was created in 1947 out of the Larissa prefecture. About 70% of the population live in the Greater **Volos** area which is the second-largest city in Thessaly and the third busiest commercial port in Greece. Much of the population lives near the **Pagasetic Gulf** and in the eastern part. The capital of Magnesia prefecture is the metropolitan city of **Volos**, one of the most scenic and developed urban areas in **Greece**. Magnesia is located only half way between **Athens** and **Thessaloniki**. As with all great discoveries the history of magnets is very colorful and interesting too.

**The Shepherd Magnes:** The most popular legend accounting for the discovery of magnets is that of an elderly Cretan shepherd named Magnes. Legend has it that Magnes was herding his sheep in an area of Northern Greece called Magnesia, about 4,000 years ago. Suddenly both, the nails in his shoes and the metal tip of his staff became firmly stuck to the large, black rock on which he was standing. To find the source of attraction he dug up the Earth to find lodestones (load = lead or attract). Lodestones contain magnetite, a natural magnetic material  $\text{Fe}_3\text{O}_4$ . This type of rock was subsequently named magnetite, after either Magnesia or Magnes himself.



**Figure 7:** The black lodestone or magnet attracting opposite pole of another magnet.

The earliest discovery of the properties of lodestone was either by the Greeks or Chinese. Stories of magnetism date back to the first century B.C in the writings of Lucretius and Pliny the Elder (23-79 AD Roman). Pliny wrote of a hill near the river Indus that was made entirely of a stone that attracted iron. He mentioned the magical powers of magnetite in his writings. For many years following its discovery, magnetite was surrounded in superstition and was considered to possess magical powers, such as the ability to heal the sick, frighten away evil spirits and attract and dissolve ships made of iron!

People believed that there were whole islands of a magnetic nature that could attract ships by virtue of the iron nails used in their construction. Ships that thus disappeared at sea were believed to have been mysteriously pulled by these islands. Archimedes is purported to have used loadstones to remove nails from enemy ships thus sinking them.

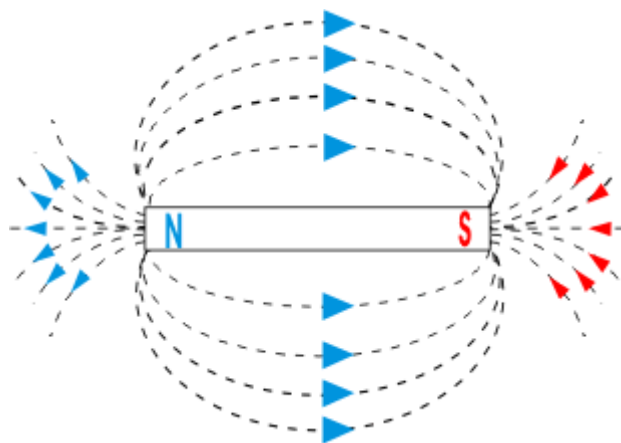
People soon realized that magnetite not only attracted objects made of iron, but when made into the shape of a needle and floated on water, magnetite always pointed in a north-south direction creating a primitive compass. This led to an alternative name for magnetite, that of lodestone or "leading stone". For many years following the discovery of lodestone magnetism was just a curious natural phenomenon. The Chinese developed the mariner's compass some 4500 years ago. The earliest mariner's compass comprised a splinter of loadstone carefully floated on the surface tension of water.

**Early Discoveries:** Peregrinus and Gilbert Peter Peregrinus is credited with the first attempt to separate fact from superstition in **1269**. Peregrinus wrote a letter describing everything that was known, at that time, about magnetite. It is said that he did this while standing guard outside the walls of Lucera which was under siege. While people were starving to death inside the walls, Peter Peregrinus was outside writing one of the first 'scientific' reports and one that was to have a vast impact on the world.

However, significant progress was made only with the experiments of **William Gilbert** in **1600** in the understanding of magnetism. It was Gilbert who first realized that the Earth was a giant magnet and that magnets could be made by beating wrought iron. He also discovered that *heating resulted in the loss of induced magnetism*.

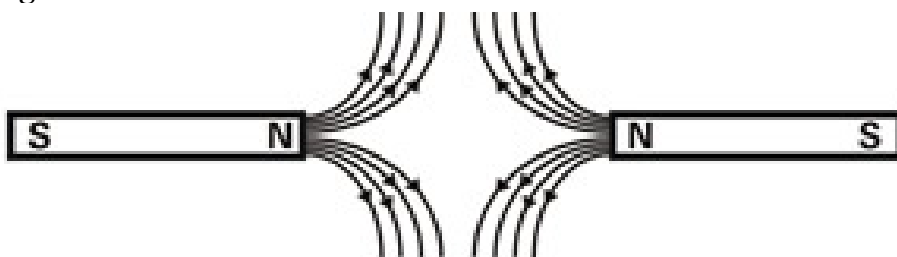
**Special properties of a Magnet:** The spinning of the electrons around the nucleus of an atom creates a tiny magnetic field. Most objects are not magnetic because the atoms are arranged so that the electrons spin in different, random directions, and cancel out each other.

Magnets are different; the molecules in magnets are arranged so that the electrons spin in the same direction. This arrangement of atoms creates two poles in a magnet, a North-seeking pole and a South-seeking pole.



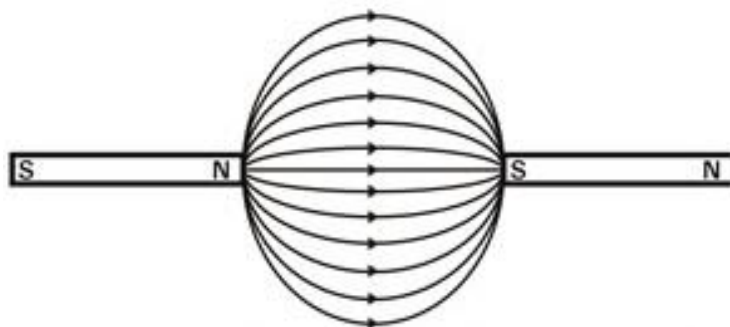
**Figure 8:** A bar magnet.

A magnet is labeled with **North (N)** and **South (S)** poles. The magnetic force in a magnet flows from the north pole to the south pole. This creates a **magnetic field** around a magnet.



**Figure 9:** Like poles of magnets (N-N or S-S) repel each other.

Have you ever held two magnets close to each other? They do not act like most objects. If you try to push the south poles together, they repel each other. Two north poles also repel each other. Now, turn one magnet around and the north (N) and the south (S) poles are attracted to each other. The magnets come together with a strong force. Just like protons and electrons, opposites attract.



**Figure 10:** Opposite poles of magnets (N-S or S-N) attract each other.

These special properties of magnets can be used to make electricity. Moving magnetic fields can pull and push electrons. Some metals, like copper have electrons that are loosely held. They can be pushed from their shells by moving magnets. Magnets and wire are used together in electric generators.

### ***3.2.2 Electricity from Magnetic Field***

An understanding of the relationship between **electricity** and magnetism began in **1819** with work by **Hans Christian Oersted** (1777-1851 Danish), a professor at the University of Copenhagen, who discovered more or less by accident that an electric current could influence a compass needle. This landmark experiment is known as **Oersted's Experiment**. In **1820** he demonstrated that magnetism was related to electricity by bringing a wire carrying an electric current close to a magnetic compass which caused a deflection of the compass needle. It is now known that whenever current flows there will be an associated magnetic field in the surrounding space, or more generally, the movement of any charged particle will produce a magnetic field.



**Figure 11:** Hans Christian Oersted.

Several other experiments followed, with **André-Marie Ampère**, **Carl Friedrich Gauss**, **Michael Faraday**, and others finding further links between magnetism and electricity.

In **1820**, **André-Marie Ampère** (1775-1836) had noticed that wires carrying an electric current were at times attracted to one another while at other times they were repelled. This discovery gave a clue to the subsequently proved intimate relationship between electricity and magnetism which was promptly followed up by **Ampère** who shortly thereafter (**1821**) announced his celebrated theory of electrodynamics, relating to the force that one current exerts upon another, by its electro-magnetic effects, namely:

1. Two parallel portions of a circuit attract one another if the currents in them are flowing in the same direction, and repel one another if the currents flow in the opposite direction.
2. Two portions of circuits crossing one another obliquely attract one another if both the currents flow either towards or from the point of crossing, and repel one another if one flows to and the other from that point.
3. When an element of a circuit exerts a force on another element of a circuit, that force always tends to urge the latter in a direction at right angles to its own direction.

**Arago** in **1824** made the important discovery that when a copper disc is rotated in its own plane, and if a magnetic needle be freely suspended on a pivot over the disc, the needle will rotate with the disc. If on the other hand ***the needle is fixed it will tend to retard the motion of the disc***. This effect was termed **Arago's rotations**.

Futile attempts were made by **Babbage, Barlow, Herschel** and others to explain this phenomenon. The true explanation was reserved for **Faraday**, namely, that *electric currents are induced in the copper disc by the cutting of the magnetic lines of force of the needle, which currents in turn react on the needle*.

In **1831** began the epoch-making researches of **Michael Faraday**, the famous **pupil** and successor of **Humphrey Davy** at the head of the Royal Institution, London, relating to electric and electromagnetic induction. Faraday's studies and researches extended from 1831 to 1855 and a detailed description of his experiments, deductions and speculations are to be found in his compiled papers, entitled 'Experimental Researches in Electricity.' Faraday was by profession a chemist. He was not in the remotest degree a mathematician in the ordinary sense — indeed it is a quest on if in all his writings there is a single mathematical formula.

### **3.2.3 Faraday's Law of Electromagnetic Induction**

A major advance in electromagnetic theory was made by **Michael Faraday** (1791-1867), who, in **1831**, discovered experimentally that a current was induced in a conducting loop when the magnetic flux linking the loop changed. He also demonstrated how a copper disc was able to provide a constant flow of electricity when revolved in a strong magnetic field (refer to Figure 15). Faraday, assisting Davy and his research team, succeeded in generating an endless electrical force as long as the movement between a coil and magnet continued. The electric generator was invented. The quantitative relationship between the induced e.m.f. and the rate of change of flux linkage, based on experimental observation, is known as Faraday's law.

**The experiment** which led Faraday to the discovery of electric induction was made as follows: He constructed what is now and was then termed an induction coil, the primary and secondary wires of which were wound on a wooden bobbin, side by side, and insulated from one another. In the circuit of the primary wire he placed a battery of approximately 100 cells. In the secondary wire he inserted a galvanometer. On making his first test he observed no results, the galvanometer remaining quiescent, but on increasing the length of the wires he noticed a deflection of the galvanometer in the secondary wire ***when the circuit of the primary wire was made and broken***. This was the first observed instance of the development of electromotive force by electromagnetic induction.

He also discovered that induced currents are established in a second closed circuit ***when the current strength is varied in the first wire***, and that the direction of the current in the secondary circuit is opposite to that in the first circuit. Also that ***a current is induced in a secondary circuit when another circuit carrying a current is moved to and from the first circuit***, and that ***the approach or withdrawal of a magnet to or from a closed circuit induces momentary currents in the latter***. In short, *within the space of a few months Faraday*

discovered by experiment virtually all the laws and facts now known concerning electro-magnetic induction and magneto-electric induction. Upon these discoveries, with scarcely an exception, depends the operation of the telephone, the dynamo machine, and incidental to the dynamo electric machine practically all the gigantic electrical industries of the world, including **electric lighting**, electric traction, the operation of electric motors, and **electro-plating, electrotyping**, etc.

Three cases will now be considered for discussing the Faraday's law.

- Case I** : A Stationary Circuit in a Time-Varying Magnetic Field.  
**Case II** : A Moving Conductor in a Static Varying Magnetic Field.  
**Case III** : A Moving Circuit in a Time-Varying Magnetic Field.

### **Case I: A Stationary Circuit in a Time-Varying Magnetic Field**

$$\oint_C \vec{E} \cdot d\vec{l} = -\frac{d}{dt} \int_S \vec{B} \cdot d\vec{S} \dots \dots \dots (2.a)$$

$$\text{or } \psi = -\frac{d\phi}{dt} \dots \dots \dots (2.b)$$

$$\text{where } \psi = \oint_C \vec{E} \cdot d\vec{l} \text{ and } \phi = \int_S \vec{B} \cdot d\vec{S}.$$

where  $\psi$  = e.m.f. induced in circuit with contour C (V)

$\Phi$  = magnetic flux crossing surface S (Wb).

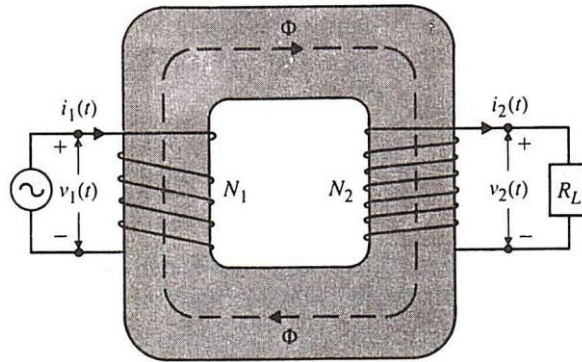
The negative sign in the above equation is an assertion that the induced e.m.f. will cause a current flow in the closed loop in such a direction as to oppose the change in the linking magnetic flux.

The e.m.f. induced in a stationary loop caused by a time-varying magnetic field is a transformer e.m.f.

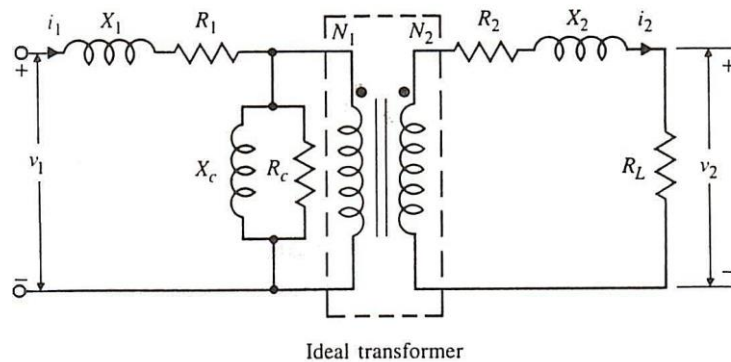
**Definition of a Transformer:** A transformer is an alternating-current (a-c) device that transforms **voltages, currents** and **impedances**. It usually consists of two or more coils coupled magnetically through a common ferromagnetic core, such as that sketched in Figure 12. Faraday's law of electromagnetic induction is the principle of operation of transformers.

**Induction Heating:** When time-varying magnetic flux flows in the ferromagnetic core, an induced e.m.f. will result in accordance with Faraday's law. This induced e.m.f. will produce local currents in the conducting core normal to the magnetic flux. These currents are called eddy currents. Eddy currents produce ohmic power loss and cause local heating. As a matter of fact, this is the principle of induction heating. Induction furnaces have been built to produce high enough temperatures to melt metals. However, in transformers this eddy-current power loss is undesirable and can be reduced by using core materials that have high permeability but low conductivity (high  $\mu$  and  $\sigma$  low). Ferrites are such materials. For low-frequency, high-power applications an economical way for reducing eddy-current power loss is to use laminated cores; that is to make transformer cores out of stacked ferromagnetic (iron) sheets, each electrically insulated from its neighbours by thin varnish or oxide

coatings. The insulating coatings are parallel to the direction of the magnetic flux so that eddy currents normal to the flux are restricted to the laminated sheets. It can be proved that the total eddy-current power loss decreases as the number of laminations increases. The amount of power-loss reduction depends on the shape and size of the cross section as well as on the method of lamination.



(a) Schematic diagram of a transformer.

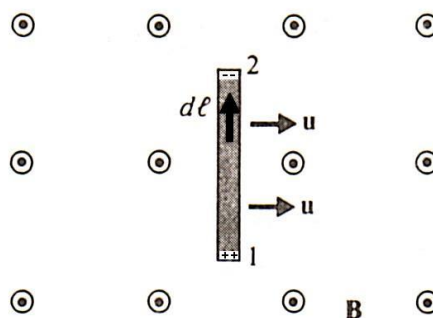


(b) An equivalent circuit.

**Figure 12:** Induced e.m.f.s in a transformer.

### ***Case II: A Moving Conductor in a Static Varying Magnetic Field***

When a conductor moves with a velocity  $u$  in a static magnetic field  $B$  (non-time varying) a force  $\mathbf{F}_m = q(\mathbf{u} \times \mathbf{B})$  will cause the freely movable electrons in the conductor to drift toward one end of the conductor and leave the other end positively charged.  $\mathbf{F}_m$  = Magnetic force.



**Figure 13:** A conductor bar moving in a static magnetic field.

The separation of positive and negative charges creates a Coulombian force of attraction. The charge separation process continues until the electric and magnetic forces balance each other and a state of equilibrium is reached. At equilibrium, (which is reached rapidly), the net force on the free charges in the moving conductor is zero. The magnetic force per unit charge  $\mathbf{F}_m/q = (\mathbf{u} \times \mathbf{B})$  can be interpreted as an induced electric field acting along the conductor and producing a voltage

$$V_{21} = \int_1^2 (\bar{\mathbf{u}} \times \bar{\mathbf{B}}) \cdot d\bar{\mathbf{l}} \dots \dots \dots (3.a)$$

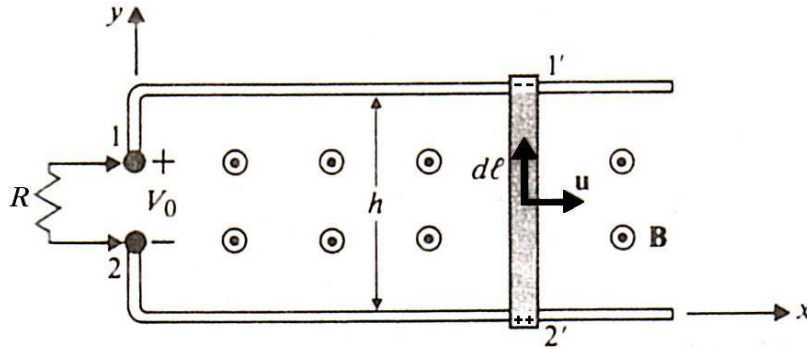
where,  $V_{21} = V_2 - V_1$ .

If the moving conductor is a part of a closed circuit C, then the e.m.f. generated around the circuit is

$$\psi = \int_C (\bar{\mathbf{u}} \times \bar{\mathbf{B}}) \cdot d\bar{\mathbf{l}} \dots \dots \dots (3.b)$$

Obviously, only part of the circuit that moves in a direction not parallel to (and hence, figuratively, “cutting”) the magnetic flux will contribute to  $\psi$  in the equation above. This is referred to as flux-cutting e.m.f. or motional e.m.f. Usually, we generate electricity using this principle.

A metal bar slides over a pair of conducting rails in a uniform magnetic field  $\mathbf{B} = \mathbf{a}_z B_0$ , with a constant velocity  $u$ .



**Figure 14:** A metal bar sliding over conducting rail.

The open circuit voltage  $V_0$  that appears across terminals 1 and 2 is given by

$$V_0 = V_1 - V_2 = -uB_0h \dots \dots \dots (4)$$

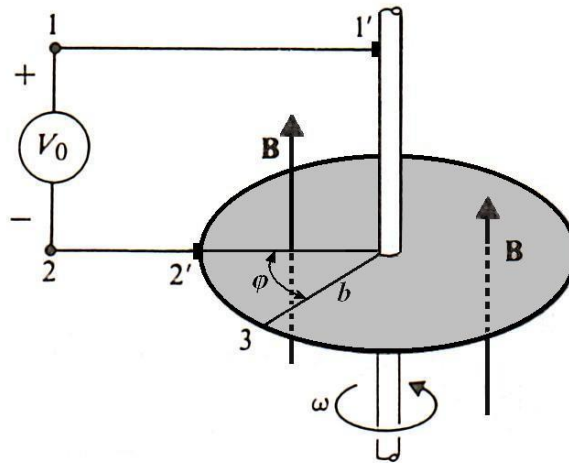
The **Faraday disk generator** consists of a circular metal disk rotating with a constant angular velocity  $\omega$  in a uniform and constant magnetic field of flux density  $\mathbf{B} = \mathbf{a}_z B_0$  that is parallel to the axis of rotation. Brush contacts are provided at the axis and on the rim of the disk as shown in Figure 15.

The open circuit voltage of the generator is given by

$$V_0 = -\frac{\omega B_0 b^2}{2} \quad (\text{V}) \dots \dots \dots (5)$$

where  $b$  is the radius of the disk.

To measure  $V_0$ , we must use a voltmeter of a very high resistance so that no appreciable current flows in the circuit to modify the externally applied magnetic field.



**Figure 15:** Faraday's disc generator.

### **Case III: A Moving Circuit in a Time-Varying Magnetic Field**

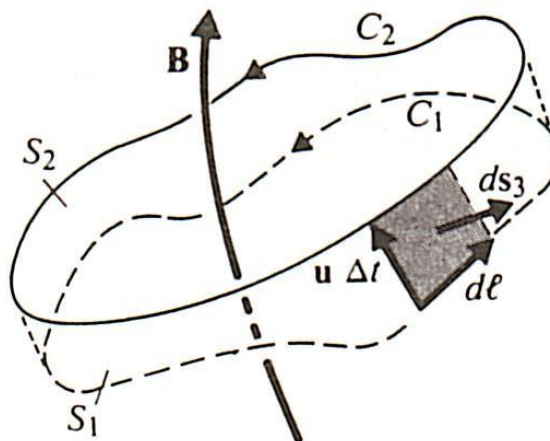
When a charge moves with a velocity  $u$  in a region where both an electric field  $E$  and a magnetic field  $B$  exist, the electromagnetic force  $F$  on  $q$ , as measured by a laboratory observer, is given by Lorenz's force equation, which is repeated below.

$$\begin{aligned}\bar{F} &= q(\bar{E} + \bar{u} \times \bar{B}) \\ &= q\bar{E}' \quad \dots \dots \dots (6)\end{aligned}$$

The force on  $q$  can be interpreted as caused by an electric field  $E'$ , where

$$\bar{E}' = \bar{E} + \bar{u} \times \bar{B} \quad \dots \dots \dots (7)$$

**Note:** Time-varying magnetic field is always coupled with time-varying electric field and vice versa.



**Figure 16:** A moving circuit in a time-varying magnetic field.

Hence, when a conducting circuit with contour C and surface S moves with a velocity  $\mathbf{u}$  in a field  $(\mathbf{E}, \mathbf{B})$ , we use  $\mathbf{E}'$  to compute  $\psi'$  as before.

$$\begin{aligned}\psi' &= \oint_C \overline{\mathbf{E}'} \cdot d\overline{\mathbf{l}} \\ &= - \int_S \frac{\partial \overline{\mathbf{B}}}{\partial t} \cdot d\overline{\mathbf{S}} + \oint_C (\overline{\mathbf{u}} \times \overline{\mathbf{B}}) \cdot d\overline{\mathbf{l}} \dots \dots \dots (8)\end{aligned}$$

where,  $\psi'$  = e.m.f. induced in the moving frame of reference (V)

The first term on the right side represents the transformer e.m.f. due to the time variation of  $\mathbf{B}$ ; and the second term represents the motional e.m.f. due to the motion of the circuit in  $\mathbf{B}$ .

*This is the general form of Faraday's law for a moving circuit in a time-varying magnetic field.*

In **1832**, **Michael Faraday** published the results of his experiment on the identity of electricity, which proved that the electricity induced using a **magnet**, voltaic electricity produced by a **battery**, and static electricity were all the same. Since Faraday's result, the history of static electricity merged with the study of electricity in general.

In **1833**, Faraday also established the foundation of **electrochemistry** with Faraday's Law, which describes the amount of reduction that occurs in an electrolytic cell.

Eventually it was James Clerk Maxwell (1831-1879 Scottish) who established beyond doubt the inter-relationships between electricity and magnetism and promulgated a series of deceptively simple equations that are the basis of electromagnetic theory today. What is more remarkable is that **Maxwell** developed his ideas in **1862** more than **thirty years before J. Thomson discovered the electron in 1897**, the *particle that is so fundamental to the current understanding of both electricity and magnetism*. **James Clerk Maxwell** synthesized and expanded these insights into **Maxwell's equations**, unifying electricity, magnetism, and **optics** into the field of **electromagnetism**. In **1905**, **Einstein** used these laws in motivating his theory of **special relativity**, requiring that the laws held true in all inertial reference frames.

The term magnetism was thus coined to explain the phenomenon whereby lodestones attracted iron. Today, after hundreds of years of research we not only know the attractive and repulsive nature of magnets, but also understand MIR scans in the field of medicine, computers chips, television and telephones in electronics and even that certain birds, butterflies and other insects have a magnetic sense of direction.

## 4. MODERN VIEWPOINT OF ELECTRICITY

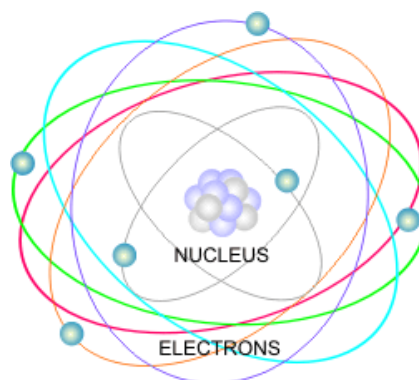
Electricity is the flow of electrical power or charge. It is a secondary energy source which means that we get it from the conversion of other sources of energy, like coal, natural gas, oil, nuclear power and other natural sources, which are called primary sources.

### 4.1 The Science of Electricity

In order to understand how electric charge moves from one atom to another, we need to know something about atoms. Everything in the universe is made of atoms—every star, every tree, every animal. The human body is made of atoms. Air and water are, too. Atoms are the building blocks of the universe. Atoms are so small that millions of them would fit on the head of a pin.

Atoms are made of even smaller particles. The center of an atom is called the **nucleus**. It is made of particles called **protons** and **neutrons**. The protons and neutrons are very small, but electrons are much, much smaller. **Electrons** spin around the nucleus in shells a great distance from the nucleus. If the nucleus were the size of a tennis ball, the atom would be the size of the Empire State Building. Atoms are mostly empty space.

If we could see an atom, it would look a little like a tiny center of balls surrounded by giant invisible bubbles (or shells). The electrons would be on the surface of the bubbles, constantly spinning and moving to stay as far away from each other as possible. Electrons are held in their shells by an electrical force.

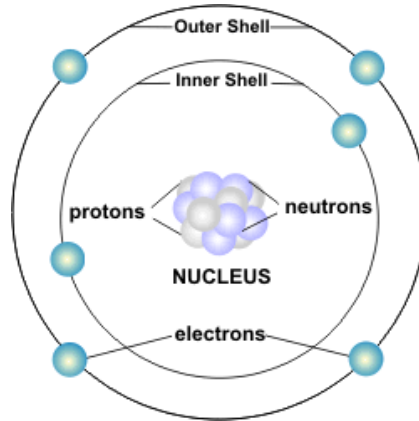


**Figure 17:** Atom – its nucleus and surrounding electrons.

The protons and electrons of an atom are attracted to each other. They both carry an **electrical charge**. An electrical charge is a force within the particle. Protons have a positive charge (+) and electrons have a negative charge (–). The positive charge of the protons is equal to the negative charge of the electrons. Opposite charges attract each other. When an atom is in balance, it has an equal number of protons and electrons. The neutrons carry no charge and their number can vary.

The number of protons in an atom determines the kind of atom, or **element**, it is. An element is a substance in which all of the atoms are identical (the **Periodic Table** shows all the known elements). Every atom of hydrogen, for example, has one proton and one electron, with no neutrons. Every atom of carbon has six protons, six electrons, and six neutrons. The number of protons determines which element it is.

Electrons usually remain a constant distance from the nucleus in precise **shells**. The shell closest to the nucleus can hold two electrons. The next shell can hold up to eight. The outer shells can hold even more. Some atoms with many protons can have as many as seven shells with electrons in them.



**Figure 18:** Inner and outer shells for electrons in an atom.

The electrons in the shells closest to the nucleus have a strong force of attraction to the protons. Sometimes, the electrons in the outermost shells do not. These electrons can be pushed out of their orbits. Applying a force can make them move from one atom to another. These **moving electrons** are **electricity**.

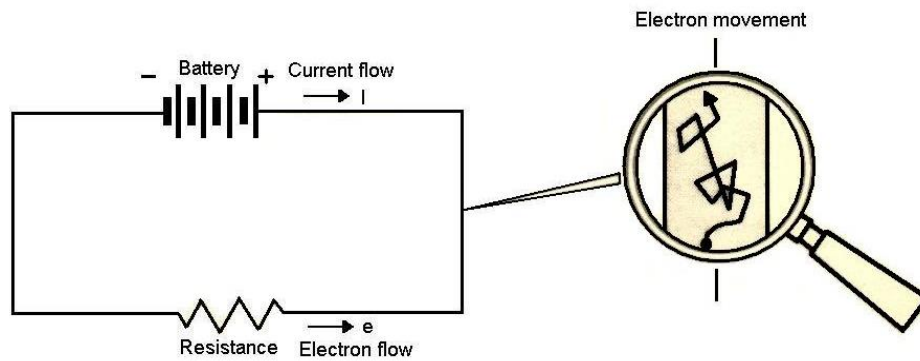
## 4.2 Electricity and Electrical signal

Generally speaking, the flow of electrons through a conductor is known as electricity. Electricity flows around a closed circuit by the driving force known as electromotive force (e.m.f.) or battery or any voltage source. The direction of electricity (known as current) is opposite to the direction of flow of electrons (Figure 19). In electronics, however, we come across another form of electricity produced by the holes (flow of equivalent positive charges as a result of absence of electrons in an atom) in a semiconductor material.

We know that

$$I = \frac{Q}{T} \dots \dots \dots (9)$$

where Q is the charge in Coulomb, T is the time in second and I is the electricity or current in Amperes. This defining equation simply tells us that if on the average Q coulombs of charge crosses across the area of cross section of a conductor per second, it produces a current of Q/T amperes through the conductor. We also know that the current is produced, primarily, as a result of flow of electrons, we may opt for the number of electrons flowing per second through the cross section of the conductor instead of the amount of charge per second.



**Figure 19:** Electron movement in a conductor: Flow of electrons through a conductor produces electrical current in the opposite direction.

Let us now calculate the number of electrons that would be equivalent to 1 Coulomb of charge. We all know that  $e = 1.609 \times 10^{-19}$  Coulomb. That is the charge of an electron is  $1.609 \times 10^{-19}$  Coulomb.

Conversely, we can say that

$1.609 \times 10^{-19}$  Coulomb charge is obtained from  $= 1$  electron.

Therefore, 1 Coulomb of charge can be obtained from  $= (1/1.609) \times 10^{19}$  electrons.

Thus if on the average  $(1/1.609) \times 10^{19}$  electrons crosses the cross-section of a conductor per second, we can say that 1 ampere (A) of current is flowing through the conductor. When this amount of electricity flows through a conductor, we measure it by using a secondary instrument (which are already calibrated by comparing with the standard values) known as **ammeter** or **galvanometer**. If the number of electrons that flow per second is half that of the said number (half of  $(1/1.609) \times 10^{19}$  electrons), the current measured would be 0.5 A; and again if the number of electrons is twice the said amount (double the  $(1/1.609) \times 10^{19}$  electrons), the current measured would be 2A. About **1850 Kirchoff** published his laws relating to branched or divided circuits. He also showed mathematically that according to the then prevailing electrodynamic theory, electricity would be propagated along a perfectly conducting wire with the velocity of light.

Electrical signal is produced as a result of variation of some physical parameter in an electrical circuit. In case of speech signal, the sounds produced by our mouth (vocal cord) are simply mechanical vibrations of air. This mechanical vibration of air has to be translated to electrical signal variation by using any suitable means. This electrical signal will then be amplified and sent through wires or by other means at a distance. Then again this electrical signal has to be converted back to sound signal there. These are done by using input transducers and output transducers.

## 5. LATER DEVELOPMENTS ON ELECTRICITY

Throughout the next hundred years, after the discovery of electricity by voltaic cell in 1800, many inventors and scientists tried to find a way to use electrical power to make light.

New discoveries were made when **Sir Humphry Davy**, inventor of the **miner's safety lamp**, installed the largest and most powerful electric battery in the vaults of the Royal Institution of London. He connected the battery to charcoal electrodes and

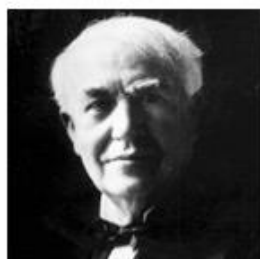
produced the first **electric light**. As reported by witnesses, his voltaic arc lamp produced *“the most brilliant ascending arch of light ever seen.”*

Davy's most important investigations were devoted to electrochemistry. Following Galvani's experiments and the discovery of the voltaic cell, interest in galvanic electricity had become widespread. Davy began to test the chemical effects of electricity in 1800. He soon found that by passing electrical current through some substances, these substances decomposed, a process later called electrolysis. The generated voltage was directly related to the reactivity of the electrolyte with the metal. Evidently, Davy understood that the actions of electrolysis and the voltaic cell were the same.

In **1879**, the American inventor **Thomas Edison** was finally able to produce a reliable, long-lasting electric light bulb in his laboratory.

### 5.1 History of the Electric Power Industry

America enjoys some of the most reliable and affordable electricity in the world. But have we ever wondered how today's electricity system, with its "on-demand" power, got its start?



**Figure 20:** Thomas Alva Edison.

In fact, any discussion about the early use of electricity would have to include Thomas Alva Edison. Although knowledge of electricity dates back to the ancient Greeks, it was not until Edison's pioneering work with electricity in the late 19th century that we were able to harness electricity in a useful way. Edison's invention of the incandescent light bulb in **1879** revolutionized our way of life and we have him to thank for the last **125 years of electric innovation**. By the end of the **1880s**, small electrical stations based on Edison's designs were in a number of U.S. cities. But each station was able to power only a few city blocks.

### 5.2 Invention of the Light bulb

On **October 21, 1879**, Edison created his now famous incandescent light bulb, which burned for 40 hours. During 1880, Edison continued work to refine his light bulb. He also began exploring ideas for an equally important invention: a way to generate and transmit the electricity his light bulb would need. A practical and reliable electricity supply was essential if the light bulb was ever to become a practical appliance for homes and businesses.

### 5.3 Edison's Pearl Street Station

By the end of **1880**, Edison had formed the **Edison Electric Illuminating Company** to build **central station electric generating plants** in **New York**

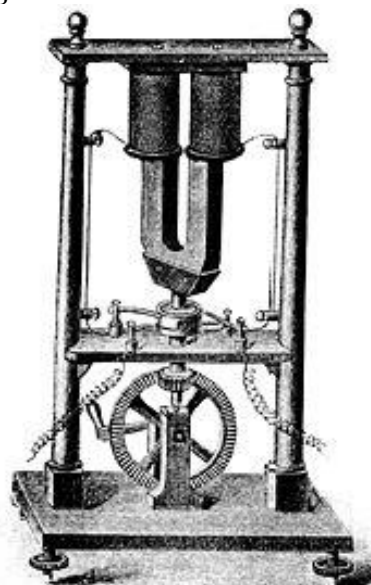
**City.** The first central power plant-Pearl Street Station in lower Manhattan-began generating electricity on **September 4, 1882**. Pearl Street had one generator and it produced power for 800 electric light bulbs. Within 14 months, Pearl Street Station had 508 subscribers and 12,732 bulbs.

With the success of Pearl Street Station, Edison created the Edison Company for Isolated Lighting. This company was formed in May 1883 to build and sell electric power stations, like Pearl Street Station, to towns and cities throughout the United States.

### ***5.3.1 How Electricity is Generated***

A generator is a device that converts mechanical energy into electrical energy. The process is based on the relationship between magnetism and electricity. As already discussed, in **1831**, **Michael Faraday** discovered that when a magnet is moved inside a coil of wire, electrical current flows in the wire. **Faraday** used a copper disk that rotated between the poles of a magnet (as shown in Figure 15) to produce electricity from his first direct current generator. The first dynamo based on Faraday's principles was built in **1832** by **Hippolyte Pixii**, a French instrument maker.

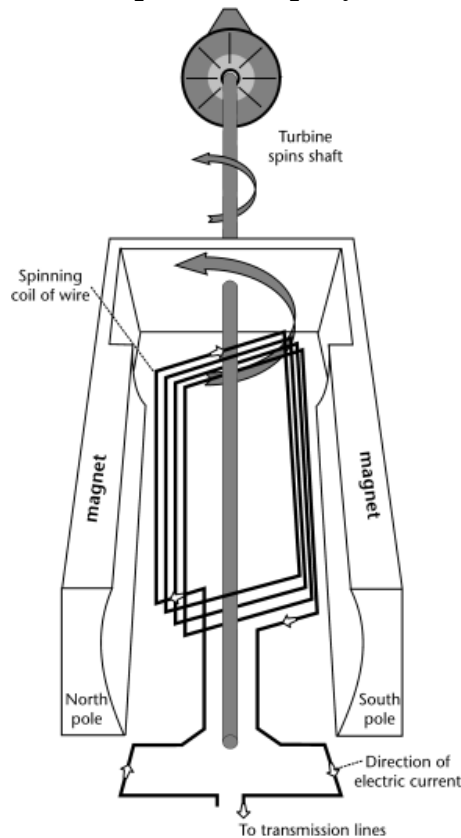
It used a **permanent magnet** which was rotated by a crank. The spinning magnet was positioned so that its north and south poles passed by a piece of iron wrapped with wire. Pixii found that the spinning magnet produced a pulse of current in the wire each time a pole passed the coil. However, the north and south poles of the magnet induced currents in opposite directions. To convert the alternating current to DC, Pixii invented a commutator, a split metal cylinder on the shaft, with two springy metal contacts that pressed against it.



**Figure 21:** Pixii's dynamo – the commutator is located on the shaft below the spinning magnet.

However, a typical generator at a power plant uses an electromagnet—a magnet produced by electricity—not a traditional magnet. The generator has a series of insulated coils of wire that form a stationary cylinder. This cylinder surrounds a rotary electromagnetic shaft. When the electromagnetic shaft rotates, it induces a small electric current in each section of the wire coil. Each section of the wire

becomes a small, separate electric conductor. The small currents of individual sections are added together to form one large current. This current is the electric power that is transmitted from the power company to the consumer.



**Figure 22:** A Turbine Generator.

An electric utility power station uses either a turbine, engine, water wheel, or other similar machine to drive an electric generator or a device that converts mechanical or chemical energy to generate electricity. Steam turbines, internal-combustion engines, gas combustion turbines, water turbines, and wind turbines are the most common methods to generate electricity. Most power plants are about 35 percent efficient. That means that for every 100 units of energy that go into a plant, only 35 units are converted to usable electrical energy.

Most of the electricity in the United States is produced in steam turbines. A turbine converts the kinetic energy of a moving fluid (liquid or gas) to mechanical energy. Steam turbines have a series of blades mounted on a shaft against which steam is forced, thus rotating the shaft connected to the generator. In a fossil-fueled steam turbine, the fuel is burned in a furnace to heat water in a boiler to produce steam. *Coal, petroleum (oil), and natural gas* are burned in large furnaces to heat water to make steam that in turn pushes on the blades of a turbine.

Most electricity generated in the United State comes from burning coal. In 2006, nearly half (49%) of the country's 4.1 trillion kilowatt-hours of electricity used coal as its source of energy.

**Natural gas**, in addition to being burned to heat water for steam, can also be burned to produce hot combustion gases that pass directly through a turbine, spinning the blades of the turbine to generate electricity. Gas turbines are commonly

used when electricity utility usage is in high demand. In 2006, 20% of the US electricity was produced by natural gas. There are other primary source options for producing electricity as well.

### **5.3.2 Discovery of Electric Motor Principles**

While not originally designed for the purpose, it was discovered that a dynamo can act as an **electric motor** when supplied with direct current from a battery or another dynamo. *At an **industrial exhibition in Vienna in 1873**, Gramme noticed that the shaft of his dynamo began to spin when its terminals were accidentally connected to another dynamo producing electricity.* Although this was not the first demonstration of an electric motor, it was the first practical one. It was found that the same design features which make a dynamo efficient also make a motor efficient. The efficient Gramme design, with small magnetic air gaps and many coils of wire attached to a many-segmented commutator, also became the basis for the design of all practical DC motors.

### **5.3.3 AC vs. DC Machines**

Edison's method for generating and transmitting electricity was called direct current, or low voltage. George Westinghouse, a consolidator of his time, built Westinghouse Electric by purchasing other inventor's patents, including the polyphase alternating current (AC) system invented by Nikola Tesla.

By this time, transformers were developed (By **William Stanley**) that could convert electricity to a desired voltage. In an alternating current system, transformers were used to step up, or increase the voltage that left the power plant. This enabled the electricity to travel over long-distance wires. When the electricity reached its destination, another transformer would then step down, or decrease the voltage so that power could be used in homes and factories.

Edison's direct current system was unable to use transformers. With Edison's system, the voltage dropped as it traveled further and further from the generator. To overcome this disadvantage, power plants would have to be built close to the power users—a costly solution.

Soon, the Westinghouse alternating current system—rather than Edison's more expensive, higher-maintenance, and less efficient direct current system—began to get most of the orders. Another advantage with the alternating system soon became apparent: By allowing central stations to serve wider markets, the AC system also encouraged utilities to build larger stations, which then benefited from economies of scale and lowered their operating costs.

In **1893**, the **Westinghouse AC system** was chosen to move electric power from Niagara Falls to Buffalo. Shortly after that, the Westinghouse AC "**universal**" system became the new standard for transmitting electricity. Now, **one generating station** could **transmit power** relatively **cheaply** over a **wide service area**.

### 5.3.4 The Transformer– for Transporting Electricity Efficiently

The maximum power transfer principle (which requires Load impedance,  $Z_{Load}$ = Line impedance,  $Z_{Line}$ ) is not used in power transmission. However, it is used extensively in low-power communication systems. Power line transmission is rather designed to operate on the principle of Maximum Efficiency, and to ensure maximum efficiency, high voltage transmission technique is employed. Efficiency  $\eta$  is defined as follows

$$\eta = \frac{P_{OUT}}{P_{GEN}} = \frac{P_{OUT}}{P_{LOSS} + P_{OUT}} \dots \dots \dots (10)$$

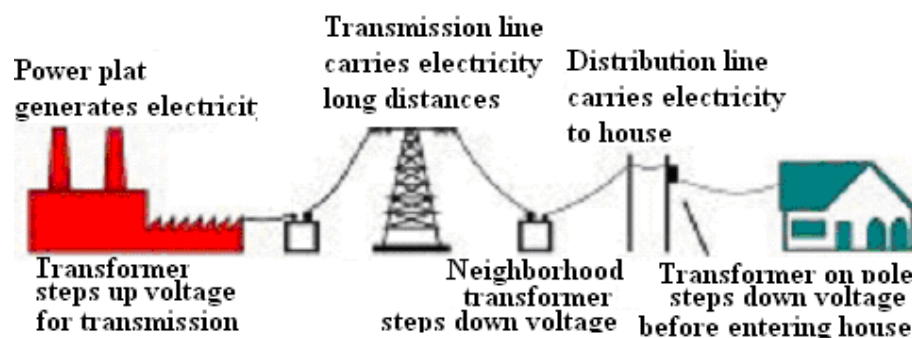
where,  $P_{OUT}$  is the power delivered to the load,  $P_{GEN}$  is the power generated, and  $P_{LOSS}$  is the total power loss in between the load and the generator.

As dynamos began to be used in industry, it was found to be more economical to transport electricity at higher voltages. ***Since power is equal to the voltage times the current, higher voltages required less current, allowing the use of narrower, less expensive conductors.***

Wire windings can conveniently produce any voltage desired by changing the number of turns, so they have been used in all dynamos. To solve the problem of sending electricity over long distances, **William Stanley** developed a device called a transformer employing Faraday's law.

The power loss in the line ( $P=I^2R$ ) depends on the resistance of the line as well as current flowing through the line. However, use of narrower but less expensive conductors must have higher resistance than a thicker radius conductor ( $R=\rho l/A$ ). However, due to the high voltage, the current in the transmission line becomes low and the square of a lower current subsides the increase in resistance of the line giving rise to a reduced overall power loss in the line.

The transformer thus allowed electricity to be efficiently transmitted over long distances. This made it possible to supply electricity to homes and businesses located far from the electric generating plant. The electricity produced by a generator travels along cables to a transformer, which changes electricity from low voltage to high voltage. Electricity can be moved long distances more efficiently using high voltage. Transmission lines are used to carry the electricity to a substation. Substations have transformers that change the high voltage electricity into lower voltage electricity. From the substation, distribution lines carry the electricity to homes, offices and factories, which require low voltage electricity.

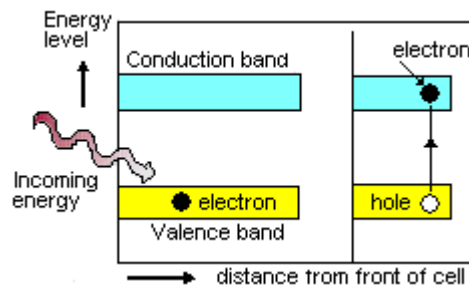
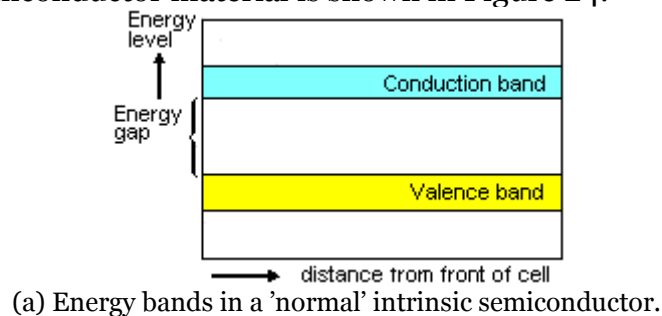


**Figure 23:** AC Power Transmission System.

Beginning about **1887** alternating current generators came into extensive operation and the commercial development of the transformer, by means of which currents of low voltage and high current strength are transformed to currents of high voltage and low current strength, and vice-versa, in time revolutionized the transmission of electric power to long distances. Likewise the introduction of the **rotary converter** (in connection with the "step-down" transformer) which converts alternating currents into direct currents (and vice-versa) has left a profound impact on the economic operation of electrical power systems.

### 5.3.5 Electrical Current in Semiconductor Materials

A semiconductor material, such as a Silicon or Germanium (Valency 4) atom has 4 valence electrons. Crystal of pure Si has a cubic structure. If some energy is added as heat or a photon of light will cause an electron to leave the inner shell and will leave a "hole" (positive charge) behind. The energy bands corresponding to an intrinsic (undoped or pure) semiconductor material is shown in Figure 24.



**Figure 24:** Energy band of a semiconductor material.

Photons must possess energy at least equal to the band gap to be 'excited' from the valence band to the conduction band. Photons with energy significantly greater will be promoted but any excess energy is dissipated as heat. That is why photovoltaic (PV) cells are not 100% efficient.

In a semiconductor transistor, there may be two types of charge carriers, namely, the 'electrons' and 'holes'. They have two different polarities and as current in a standard semiconductor transistor constitutes the flow of electrons and flow of holes, it is known as bipolar junction transistor.

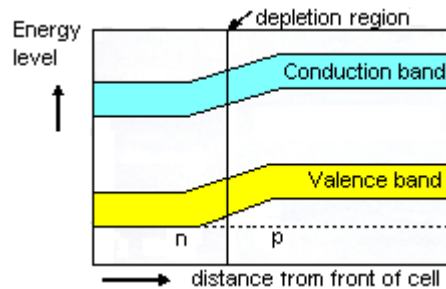
**P-type** silicon can be created by doping silicon with trace amounts of boron – with **only 3 valence electrons**. It will snatch an inner-shell electron of a silicon atom to make the bond and a 'hole' is produced. A 'hole' is a deficit of electron in the inner shell of an atom. An **N-type** silicon can be created by doping silicon with trace amounts of phosphorous – **with 5 valence electrons**. Hence an excess of free

electrons. Joining these two semiconductors forms a **p-n junction**. Negatively charged particles i.e. 'electrons' will move to p-type part and 'holes' to n-type part creating a potential difference or barrier at the junction. Solar energy is produced now-a-days by silicon solar cells, which is nothing but a big-sized p-n junction (Figure 25).

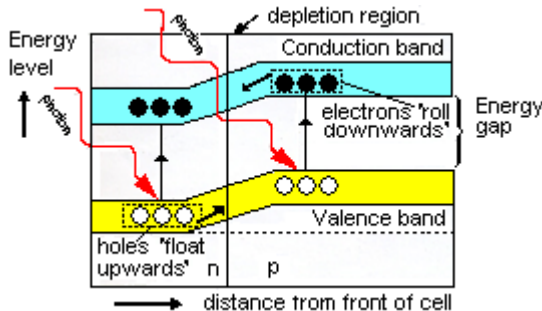


**Figure 25:** A photovoltaic solar cell.

The energy bands corresponding to a p-n doped semiconductor material is shown in Figure 26.



(a) When the n-type and p-type semiconductors are combined into a p-n junction, their different energy bands combine to give a new distribution, as shown, and a built-in electric field is created.



(b) In the p-n junction photons of light can excite electrons from the valence band to the conduction band. The electrons 'roll downwards' to the n-region, and the holes 'float upwards' to the p-region.

**Figure 26:** Energy band of a semiconductor material.

**Solar power** is derived from the energy of the sun. However, the sun's energy is not available full-time and it is widely scattered. Photovoltaic conversion generates electric power directly from the light of the sun in a photovoltaic (solar) cell. Solar-thermal electric generators use the radiant energy from the sun to produce steam to drive turbines. In 2006, less than 1% of the US electricity was based on solar power.

### 5.3.6 Electricity from Thermocouples

Professor **Seebeck**, of Berlin, in **1821** discovered that when heat is applied to the junction of two metals that had been soldered together **an electric current is set up**. This is termed **Thermo-Electricity**. Seebeck's device consists of **a strip of copper** bent at each end and soldered to a plate of **Bismuth**. A magnetic needle is placed parallel with the copper strip. When the heat of a lamp is applied to the junction of the copper and bismuth an electric current is set up which deflects the needle.

**Peltier** in **1834** discovered an effect opposite to the foregoing, namely, that when a current is passed through a couple of dissimilar metals the temperature is lowered or raised at the junction of the metals, depending on the direction of the current. This is termed the **Peltier "effect"**. The **variations of temperature arc** found to be proportional to the strength of the current and not to the square of the strength of the current as in the case of heat due to the ordinary resistance of a conductor. This latter is the **C2R law**, discovered experimentally in 1841 by the English physicist, **Joule**. In other words, this important law is that the heat generated in any part of an electric circuit is directly proportional to the product of the resistance of this part of the circuit and to the square of the strength of current flowing in the circuit.

## 6. CONCLUSIONS

This article has described the basics of electricity – from its definition, through generation to its practical use. However, we should be aware of the fact that the electricity is only a secondary form of energy. The generation of electricity depends entirely upon the primary sources of energy, namely, the non-renewable reserves and the renewable energy sources. The reserve for the non-renewable sources are depleting very fast. Therefore, first of all, we should take good care of making proper use of electricity, and under no circumstances, should we misuse it. Next, we should put all our efforts to make the maximum use of the renewable sources of energy for producing electricity. We should also focus our attention to foster research on increasing efficient electricity generation schemes of the renewable sources and use energy saving devices or appliances from now on. Conducting extensive research on generating solar electricity and fuel cells is the requirement of the time. If proper safety can be guaranteed, the nuclear power is the main option at hand now to meet the growing energy crisis.

## References

- [1] Mohammed Azizul Islam, “**Electromagnetic Theory**”, 1969, East Pakistan University of Engineering and Technology, Dacca (Now, Bangladesh University of Engineering and Technology, Dhaka).
- [2] David K. Cheng, “**Field and Wave Electromagnetics**”, Second Edition, Pearson Education, Addison Wesley Series in Electrical Engineering (ISBN 81-7808-386-8).
- [3] <http://www.eia.doe.gov/kids/energyfacts/sources/electricity.html> Internet Site
- [4] <http://www.wikipedia.org> Internet site
- [5] <http://www.buchmann.ca> Internet Site