Applied Physics

(BCS/IT-1st Semester)

Electric Charge:

Electric Charge is nothing but the amount of energy or electrons that pass from one body to another by different modes like conduction, induction or other specific methods. This is a basic electric charge definition. There are two types of electric charges. They are positive charges and negative charges.

Charges are present in almost every type of body. All those bodies having no charges are the neutrally charged ones. We denote a charge y the symbol 'q' and its standard unit is Coulomb. Mathematically, we can say that a charge is the number of electrons multiplied by the charge on 1 electron. Symbolically, it is

$Q = ne$

where q is a charge, n is a number of electrons and e is a charge on 1 electron (1.6×10^{-19}C). The two very basic natures of electric charges are

- Like charges repel each other.
- Unlike charges attract each other.

This means that while protons repel protons, they attract electrons. The nature of charges is responsible for the forces acting on them and coordinating the direction of the flow of them. The charge on electron and proton is the same in magnitude which is 1.6×10^{-19} C. The difference is only the sign that we use to denote them, + and –

Electric charge is quantized

Quantization of charge implies that charge can assume only certain discrete values. That is to say the observed value of electric charge (q) of a particle will be integral multiples of (e) 1.6×10^{-19} coulombs. i.e.

$q= ne$ where $n= 0,1,2,....$ (both positive and negative integers)

The charge cannot assume any value between the integers.

Electric Charge is Conserved

Because the fundamental positive and negative units of charge are carried on protons and electrons, we would expect that the total charge cannot change in any system that we define. In other words, although we might be able to move charge around, we cannot create or destroy it. This should be true provided that we do not create or destroy protons or electrons in our system. In the twentieth century, however, scientists learned how to create and destroy electrons and protons, but they found that charge is still conserved. Many experiments and solid theoretical arguments have elevated this idea to the status of a law. The law of conservation of charge says that electrical charge cannot be created or destroyed.

The law of conservation of charge is very useful. It tells us that the net charge in a system is the same before and after any interaction within the system. Of course, we must ensure that no external charge enters the system during the interaction and that no internal charge leaves the system. Mathematically, conservation of charge can be expressed as

$$Q_{initial}=Q_{final}$$

where $Q_{initial}$ is the net charge of the system before the interaction, and Q_{final}, is the net charge after the interaction.

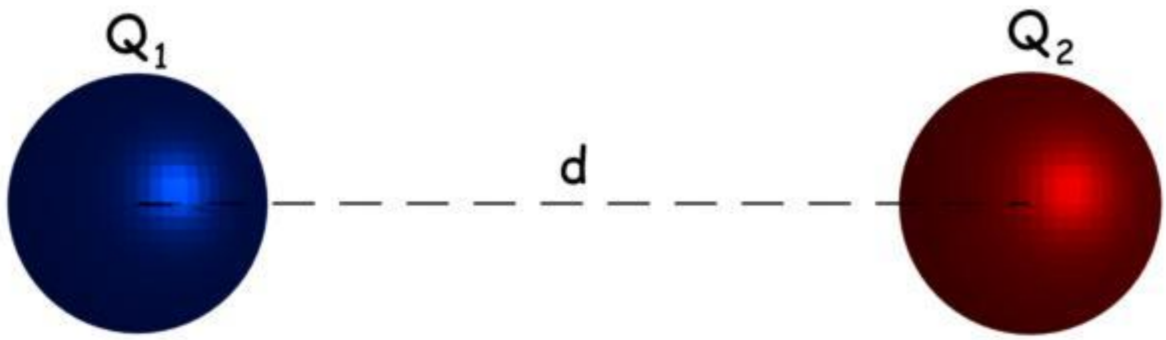
Coulomb's Law

If two electrically charged bodies are placed nearby each other there will be an attraction or a repulsion force acting on them depending upon the nature of the charge of the bodies. The formula for the force acting between two electrically charged bodies was first developed by Charles-Augustin de Coulomb and the formula he established for determining the value of force acting to nearby charged objects is known as Coulomb's law.

In his law, he stated that, similarly charged (either positive or negative) bodies will repeal each other and two dissimilarly charged bodies (one is positively charged and other is negatively charged) will attract each other. He had also stated that the force acting between the electrically charged bodies is proportional to the product of the charge of the charged bodies and inversely proportional to the square of the distance between the center of the charged bodies.

Coulomb's Law Formula

Let us imagine, Q_1 and Q_2 are the electrical charges of two objects.
d is the distance between the center of the objects.

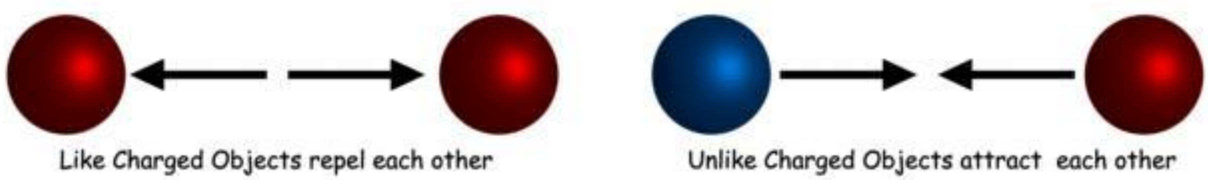


The charged objects are placed in a medium of permittivity $\varepsilon_o\varepsilon_r$, Then we can write the force 'F' as:

$$F = \frac{Q_1\ Q_2}{4\pi\epsilon_o\epsilon_r\ d^2}$$

Statement of Coulomb's Law

First Law



Like charged objects (bodies or particles) repel each other and unlike charged objects (bodies or particles) attract each other.

Second Law

The force of attraction or repulsion between two electrically charged objects is directly proportional to the magnitude of their charge and inversely proportional to the square of the distance between them. Hence, according to the Coulomb's second law,

$$F \propto Q_1\ Q_2\ \ \&\ \ F \propto \frac{1}{d^2}$$

$$\Rightarrow F \propto \frac{Q_1\ Q_2}{d^2} \Rightarrow F = k\frac{Q_1\ Q_2}{d^2}$$

Where,
'F' is the repulsion or attraction force between two charged objects.
'Q1' and 'Q2' are the electrical charged of the objects.
'd' is distance between center of the two charged objects.
'k' is a constant that depends on the medium in which charged objects are placed. In S.I. system, as well as in M.K.S. system k=1/4πεoεr. Hence, the above equation becomes.

$$F = \frac{Q_1\ Q_2}{4\pi\epsilon_o\epsilon_r\ d^2}$$

The value of $\varepsilon_o = 8.854 \times 10^{-12}\ C^2/Nm^2$.

$$Now,\ F = \frac{Q_1\ Q_2}{4\pi \times\ 8.854\ 10^{-12} \times \epsilon_r\ d^2}$$

$$= 8.9878\ \times\ 10^9 \left[\frac{Q_1\ Q_2}{\epsilon_r\ d^2}\right] \approx 9\ \times\ 10^9 \left[\frac{Q_1\ Q_2}{\epsilon_r\ d^2}\right]$$

Hence, Coulomb's law can be written for medium as,

$$F_{medium} = 9\ \times\ 10^9 \left[\frac{Q_1\ Q_2}{\epsilon_r\ d^2}\right]$$

Then, in air or vacuum $\varepsilon_r = 1$. Hence, Coulomb's law can be written for air medium as,

$$F_{air} = 9\ \times\ 10^9 \left[\frac{Q_1\ Q_2}{d^2}\right]$$

Permittivity of free space:

The permittivity of free space, ε_0, is a physical constant used often in electromagnetism. It represents the capability of a vacuum to permit electric fields.

Relative permittivity:

Relative permittivity is defined as the permittivity of a given material relative to that of the permittivity of a vacuum. It is normally symbolised by: ε_r

Relationship between ε_0 and ε_r :

$\boldsymbol{\varepsilon_r} = \boldsymbol{\varepsilon} / \varepsilon_0$
where Er is the relative permitivity of the medium
ε is the permittivity of the medium
ε_0 is the permittivity of the free space(Vacuum)

Electric Field

An electric charge produces an electric field, which is a region of space around an electrically charged particle or object in which an electric charge would feel force. The electric field exists at all points in space and can be observed by bringing another charge into the electric field. However, the electric field can be approximated as zero for practical purposes if the charges are far enough from each other.

Electric fields are a vector quantity and can be visualized as arrows going toward or away from charges. The lines are defined as pointing radially outward, away from a positive charge, or radially inward, toward a negative charge.

The magnitude of the electric field is given by the formula:

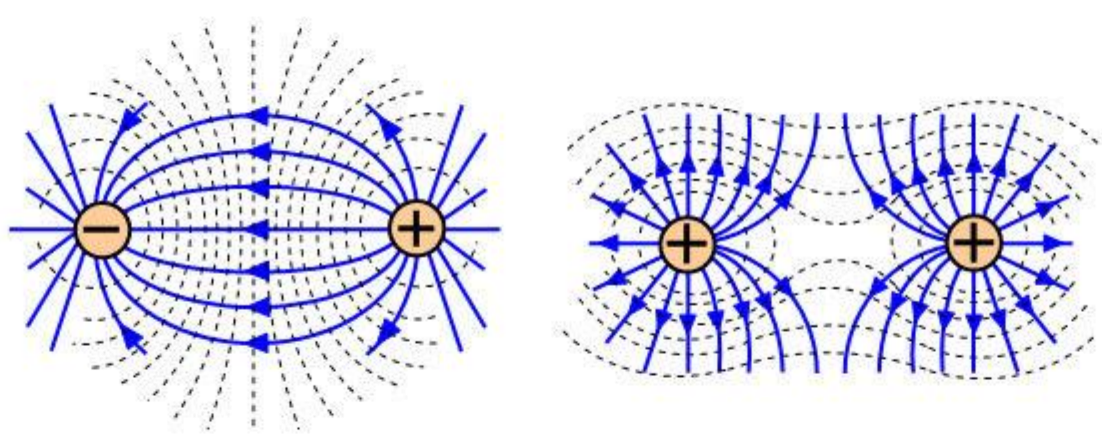
$$\vec{E} = \frac{\vec{F}}{Q}$$

where $\vec{E}$ is the strength of the electric field,
$\vec{F}$ is the electric force,
and Q is the test charge that is being used to “feel” the electric field.

- Electric Field ($\vec{E}$) and Electric Force $\vec{F}$are in same direction.
- For positive charges the direction is outward as repulsion.
- For negative charges the direction is inward as attraction.

Electric Field Lines:

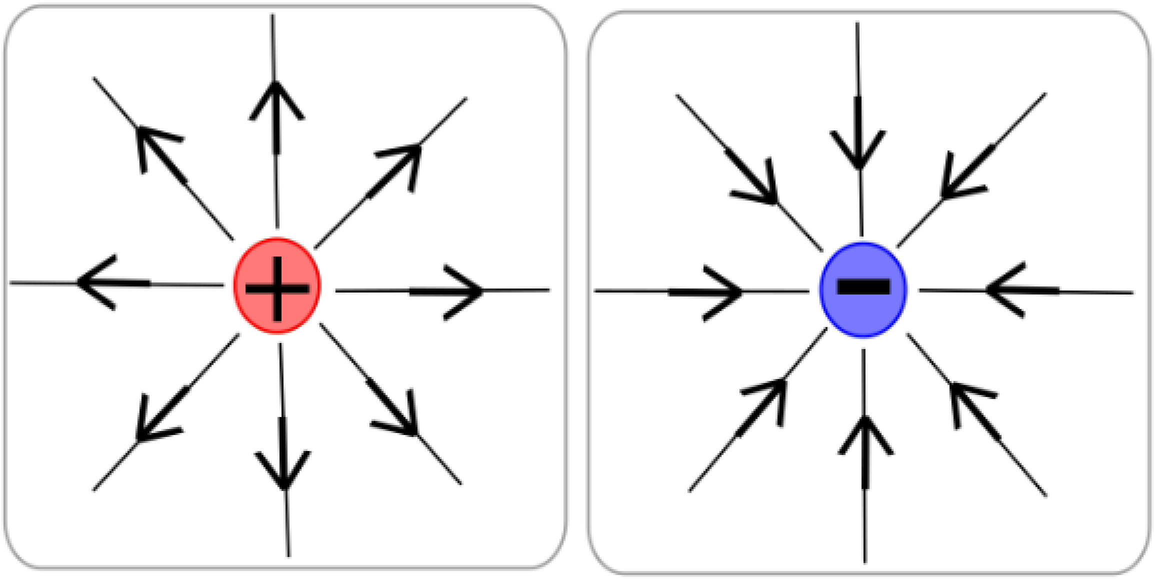
electric charges create an electric field in the space surrounding them. It acts as a kind of "map" that gives that gives the direction and indicates the strength of the electric field at various regions in space. The concept of electric field lines was introduced by Michael Faraday, which helped him to easily visualize the electric field using intuition rather than mathematical analysis.



Properties of Electric Field Lines

- The field lines never intersect each other.
- The field lines are perpendicular to the surface of the charge.
- The magnitude of charge and the number of field lines, both are proportional to each other.
- The start point of the field lines is at the positive charge and end at the negative charge.

Electric field lines always point away from a positive charge and towards a negative point. In fact, electric fields originate at a positive charge and terminate at a negative charge.



Electric Field of Point Charge

To find the electric field due to a charged particle (often called a point charge), we place a positive test charge at any point near the particle, at distance r. From Coulomb's law the force on the test charge due to the particle with charge q is

$$\vec{F} = \frac{1}{4\pi\varepsilon_0} \frac{q q_0}{r^2} \hat{\mathrm{r}} .$$

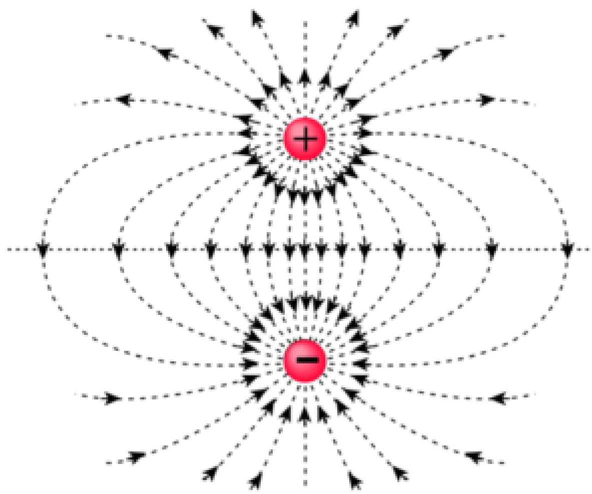
as previously discussed, the direction of F is directly away from the particle if *q* is positive (because q_0 is positive) and directly toward it if q is negative. we can now write the electric field set up by the particle (at the location of the test charge) as

$$\vec{E} = \frac{\vec{F}}{q_0} = \frac{1}{4\pi\varepsilon_0} \frac{q}{r^2} \hat{\mathrm{r}} \quad \text{(charged particle).}$$

Electric Dipole

Electric charge is present around us and there are many different examples to prove this phenomenon. Have you ever tried rubbing a comb-over a towel and brought it close to your hair? You will see that some of your hair tend to get attracted to the comb. This is basically due to the generation of Electric Charge. In this section, we will try to decode the behavior of opposite charges when kept at a distance. This is the concept of the Electric Dipole which is a vital portion of electrostatics.

Introduction to Electric Dipole



An electric dipole is tagged as a pair of objects which possess equal & opposite charges, parted by a significantly small distance. Let us take two charges having equal magnitude ‘Q’, which are separated by the distance ‘D’.

Here we assume the first charge to be negative, while the second charge stays positive. You can call this particular combination as an electric dipole. Hence, we can state that an electric dipole is formed due to the grouping of equal & opposite charges when separated by an assured distance

What is the Dipole Moment?

It is basically the exact measure of the strength associated with an electric dipole. Based on scientific and mathematical conclusions, the dipole moment magnitude is the product of either of the charges and the separation distance (d) between them. Do remember that, the dipole moment is a vector measure whose direction runs from negative to a positive charge.

The formula for electric dipole moment for a pair of equal & opposite charges is $\mathbf{p} = q*\mathbf{d}$, the magnitude of the charges multiplied by the distance between the two.

Electric Potential and Electric Potential Energy

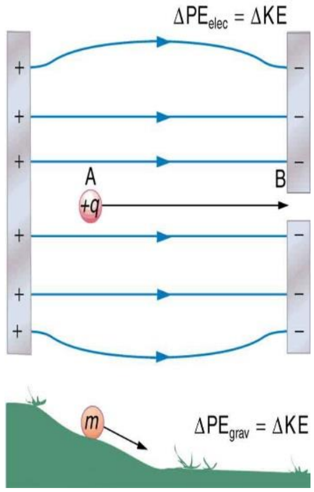
We are going to define the electric potential (or potential for short) in terms of electric potential energy, so our first job is to figure out how to measure that potential energy. Back in Chapter 8, we measured gravitational potential energy U of an object by (1) assigning U = 0 for a reference configuration (such as the object at table level) and (2) then calculating the work W the gravitational force does if the object is moved up or down from that level. We then defined the potential energy as being

U =-W (potential energy).

Let's follow the same procedure with our new conservative force, the electric force. In Fig. 24-2a, we want to find the potential energy U associated with a positive test charge q0 located at point P in the electric field of a charged rod. First, we need a reference configuration for which U $ 0. A reasonable choice is for the test charge to be infinitely far from the rod, because then there is no interaction with the rod. Next, we bring the test charge in from infinity to point P to form the configuration of Fig. 24-2a. Along the way, we calculate the work done by the electric force on the test charge. The potential energy of the final configuration is then given by Eq. 24-1, where W is now the work done by the electric force. Let's use the notation to emphasize that the test charge is brought in from infinity. The work and thus the potential energy can be positive or negative depending on the sign of the rod's charge. Next, we define the electric potential V at P in terms of the work done by the electric force and the resulting potential energy.

Electric Potential Energy and Potential Difference

When a free positive charge q is accelerated by an electric field, such as shown in Figure 1, it is given kinetic energy. The process is analogous to an object being accelerated by a gravitational field. It is as if the charge is going down an electrical hill where its electric potential energy is converted to kinetic energy. Let us explore the work done on a charge q by the electric field in this process, so that we may develop a definition of electric potential energy.



The electrostatic or Coulomb force is conservative, which means that the work done on q is independent of the path taken. This is exactly analogous to the gravitational force in the absence of dissipative forces such as friction. When a force is conservative, it is possible to define a potential energy associated with the force, and it is usually easier to deal with the potential energy (because it depends only on position) than to calculate the work directly.

We use the letters PE to denote electric potential energy, which has units of joules (J). The change in potential energy, ΔPE, is crucial, since the work done by a conservative force is the negative of the change in potential energy; that is, W = –ΔPE. For example, work W done to accelerate a positive charge from rest is positive and results from a loss in PE, or a negative ΔPE. There must be a minus sign in front of ΔPE to make W positive. PE can be found at any point by taking one point as a reference and calculating the work needed to move a charge to the other point.

POTENTIAL ENERGY

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Gravitational potential energy and electric potential energy are quite analogous. Potential energy accounts for work done by a conservative force and gives added insight regarding energy and energy transformation without the necessity of dealing with the force directly. It is much more common, for example, to use the concept of voltage (related to electric potential energy) than to deal with the Coulomb force directly.

Calculating the work directly is generally difficult, since $W = Fd \cos \theta$ and the direction and magnitude of F can be complex for multiple charges, for odd-shaped objects, and along arbitrary paths. But we do know that, since $F = qE$, the work, and hence ΔPE, is proportional to the test charge q. To have a physical quantity that is independent of test charge, we define electric potential V (or simply potential, since electric is understood) to be the potential energy per unit charge
$V = PE / q$

ELECTRIC POTENTIAL

This is the electric potential energy per unit charge.

$$V = PE / q$$

Since PE is proportional to q , the dependence on q cancels. Thus V does not depend on q. The change in potential energy ΔPE is crucial, and so we are concerned with the difference in potential or potential difference ΔV between two points, where

$$\Delta V = V_B - V_A = \Delta PE / q$$

The potential difference between points A and B, $V_B - V_A$, is thus defined to be the change in potential energy of a charge q moved from A to B, divided by the charge. Units of potential difference are joules per coulomb, given the name volt (V) after Alessandro Volta.

$1V = 1J/ C$

POTENTIAL DIFFERENCE

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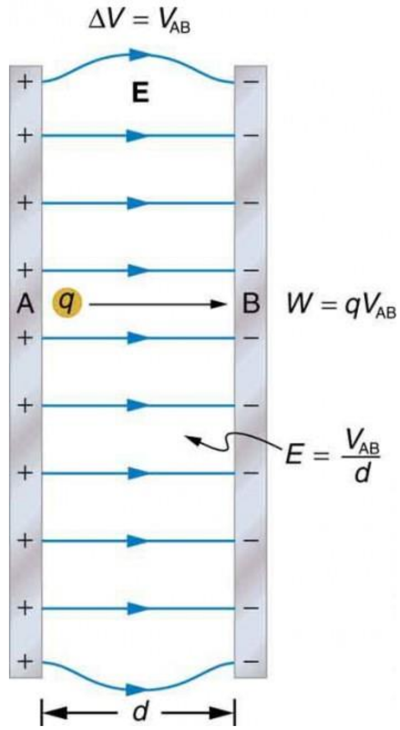
Electric Potential in a Uniform Electric Field



In the previous section, we explored the relationship between voltage and energy. In this section, we will explore the relationship between voltage and electric field. For example, a uniform electric field E is produced by placing a potential difference (or voltage) ΔV across two parallel metal plates, labeled A and B. (See Figure 1.)

Examining this will tell us what voltage is needed to produce a certain electric field strength; it will also reveal a more fundamental relationship between electric potential and electric field. From a physicist's point of view, either ΔV or E can be used to describe any charge distribution. ΔV is most closely tied to energy, whereas E is most closely related to force. ΔV is a scalar quantity and has no direction, while E is a vector quantity, having both magnitude and direction. (Note that the magnitude of the electric field strength, a scalar quantity, is represented by E below.) The relationship between ΔV and E is revealed by calculating the work done by the force in moving a charge from point A to point B.

The work done by the electric field in Figure 1 to move a positive charge q from A, the positive plate, higher potential, to B, the negative plate, lower potential, is

$- \Delta V = WAB / q$

$WAB = - q \Delta V$

The potential Difference between point A and B is:

$-\Delta V = -(V_B - V_A) = V_A - V_B = V_{AB}.$

Entering this into the expression for work yields $W = qV_{AB}$.

Work is W = Fd cos θ; here cos θ = 1, since the path is parallel to the field, and so W = Fd.

Since F = qE, we see that W = qEd.

Substituting this expression for work into the previous equation gives:

$qEd = qV_{AB}.$

The charge cancels, and so the voltage between points A and B is seen to be

$V_{AB} = Ed$

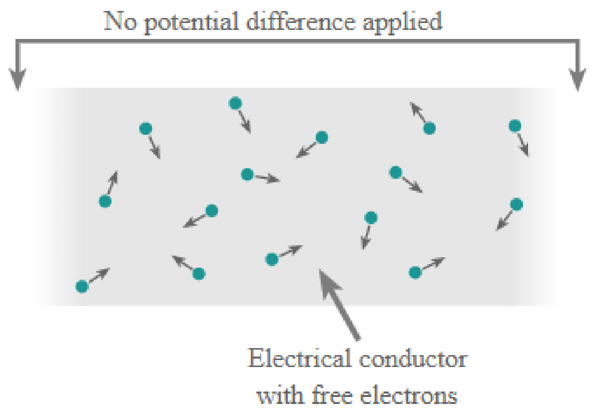
What is electric current: The basics

The basic concept of current is that it is the movement of electrons within a substance. Electrons are minute particles that exist as part of the molecular structure of materials. Sometimes these electrons are held tightly within the molecules and other times they are held loosely and they are able to move around the structure relatively freely.

One very important point to note about the electrons is that they are charged particles - they carry a negative charge. If they move then an amount of charge moves and this is called current.

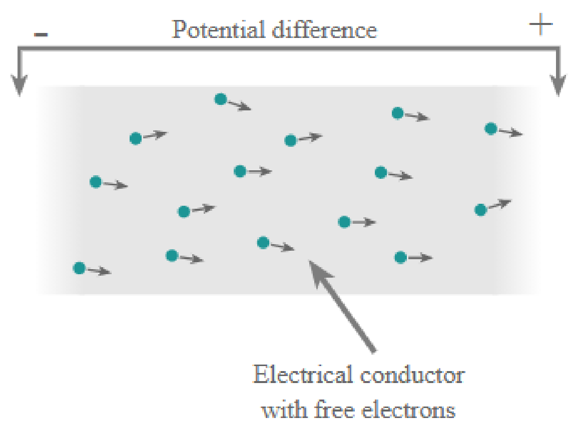
It is also worth noting that the number of electrons that able to move governs the ability of a particular substance to conduct electricity. Some materials allow current to move better than others.

The motion of the free electrons is normally very haphazard - it is random - as many electrons move in one direction as in another and as a result there is no overall movement of charge.



Random electron movement in a conductor with free electrons

If a force acts on the electrons to move them in a particular direction, then they will all drift in the same direction, although still in a somewhat haphazard fashion, but there is an overall movement in one direction.



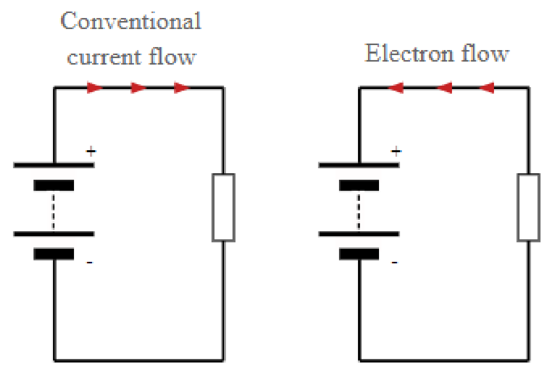
Electron flow under the action of applied electro-motive force

The force that acts on the electrons is called and electromotive force, or EMF, and its quantity is voltage measured in volts.

Conventional current and electron flow

There is often a lot of misunderstanding about conventional current flow and electron flow. This can be a little confusing at first but it is really quite straightforward.

The particles that carry charge along conductors are free electrons. The electric field direction within a circuit is by definition the direction that positive test charges are pushed. Thus, these negatively charged electrons move in the direction opposite the electric field.



Electron and conventional current flow

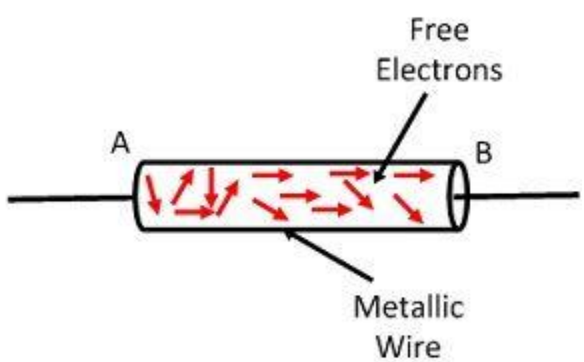
This came about because the initial investigations in static and dynamic electric currents was based upon what we would now call positive charge carriers. This meant that then early convention for the direction of an electric current was established as the direction that positive charges would move. This convention has remained and it is still used today.

In summary:

Conventional current flow: The conventional current flow is from positive to the negative terminal and indicates the direction that positive charges would flow.
Electron flow: The electron flow is from negative to positive terminal. Electrons are negatively charged and are therefore attracted to the positive terminal as unlike charges attract.

Unit of Current

Since the charge is measured in coulombs and time in seconds, so the unit of electric current is coulomb/Sec (C/s) or amperes (A). The amperes is the SI unit of the conductor. The I is the symbolic representation of the current.



Types of Current

The current can be divided into two types.

Direct Current:

- Direct current travels towards the same direction at all points, although the instantaneous magnitude can differ.
- An example of DC is the current generated by an electrochemical cell.

Alternating Current:

- The flow of charge carriers is towards the opposite direction periodically in an alternating current.
- The number of AC cycles per second is known as frequency and calculated in Hertz.

What is Current Density?

The amount of electric current traveling per unit cross-section area is called as current density and expressed in amperes per square meter. More the current in a conductor, the higher will be the current density. However, the current density alters in different parts of an electrical conductor and the effect takes place with alternating currents at higher frequencies.

Electric current always creates a magnetic field. Stronger the current, more intense is the magnetic field. Varying AC or DC creates an electromagnetic field and this is the principle based on which signal propagation takes place.

Current density is a vector quantity having both a direction and a scalar magnitude. The electric current flowing through a solid having units of charge per unit time is calculated towards the direction perpendicular to the flow of direction.

It is all about the amount of current flowing across the given region.

Current Density Formula

The formula for Current Density is given as,

$$J = I / A$$

Where,

I = current flowing through the conductor in Amperes

A = cross-sectional area in m2.

Current density is expressed in A/m2.

Current Density Calculation Example

Determine the current density when 40 Amperes of current is flowing through the battery in a given area of 10 m2.

Solution:

It is given that,

I = 40 A,

Area = 10 m^2

The current density formula is given by,

J = I / A

= 40 / 10

J = 4 A/m^2.

RESISTANCE:

Resistance (also known as ohmic resistance or electrical resistance) is a measure of the opposition to current flow in an electrical circuit. Resistance is measured in ohms, symbolized by the Greek letter omega (Ω).

Unit of Resistance

From the definition of resistance, it can be said that the unit of electric resistance is volt per ampere. One unit of resistance is such a resistance which causes 1 ampere current to flow through it when 1 volt potential difference is applied across the resistance.

The unit of electric resistance that is volt per ampere is called ohm(Ω) after the name of great

$$\frac{1\ volt}{1\ ampere} = 1\ ohm(\Omega)$$

German physicist George Simon Ohm. He is famous for his law called Ohm's law which is applicable only on pure resistance. The unit ohm is normally used for moderate values of resistance but there may be a very large as well as a very small value of resistance used for different purposes.

These values are expressed in giga-ohm, megaohm, kilo-ohm, milli-ohm, micro-ohm even in nano-ohm range depending on the value of resistance.

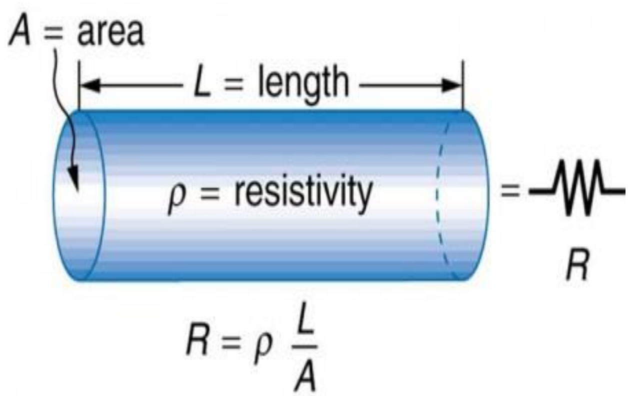
Effect of Temperature on Resistance

In metallic substances with rising temperatures the interatomic vibrations increase and hence offer more resistance to the movement of electrons causing the current. Hence, with increasing temperature the resistance of metallic substances increases.

The temperature coefficient of resistance is positive for these materials. In semiconductors with increasing temperature, the number of free electrons increases as at higher temperature more number of covalent bonds gets broken to contribute free electrons in the substance.
This reduces the resistance of the substance. Hence semiconductors have a negative temperature coefficient of resistance.

Material and Shape Dependence of Resistance

The resistance of an object depends on its shape and the material of which it is composed. The cylindrical resistor in Figure 1 is easy to analyze, and, by so doing, we can gain insight into the resistance of more complicated shapes. As you might expect, the cylinder's electric resistance R is directly proportional to its length L, similar to the resistance of a pipe to fluid flow. The longer the cylinder, the more collisions charges will make with its atoms. The greater the diameter of the cylinder, the more current it can carry (again similar to the flow of fluid through a pipe). In fact, R is inversely proportional to the cylinder's cross-sectional area A.



For a given shape, the resistance depends on the material of which the object is composed. Different materials offer different resistance to the flow of charge. We define the *resistivity* ρ of a substance so that the **resistance** R of an object is directly proportional to ρ. Resistivity ρ is an *intrinsic* property of a material, independent of its shape or size. The resistance R of a uniform cylinder of length L, of cross-sectional area A, and made of a material with resistivity ρ, is

$$R=\rho\, L / A.$$

Conductors have the smallest resistivities, and insulators have the largest; semiconductors have intermediate resistivities. Conductors have varying but large free charge densities, whereas most charges in insulators are bound to atoms and are not free to move. Semiconductors are intermediate, having far fewer free charges than conductors, but having properties that make the number of free charges depend strongly on the type and amount of impurities in the semiconductor.

Ohm’s Law

Georg Ohm found that, at a constant temperature, the electrical current flowing through a fixed linear resistance is directly proportional to the voltage applied across it, and also inversely proportional to the resistance. This relationship between the Voltage, Current and Resistance forms the basis of Ohms Law and is shown below.

$$\text{Current}, (I) = \frac{\text{Voltage}, (V)}{\text{Resistance}, (R)} \text{ in Amperes}, (A)$$

By knowing any two values of the Voltage, Current or Resistance quantities we can use Ohms Law to find the third missing value. Ohms Law is used extensively in electronics formulas and calculations so it is “very important to understand and accurately remember these formulas”.

To find the Voltage, (V)

[V = I x R]   V (volts) = I (amps) x R (Ω)

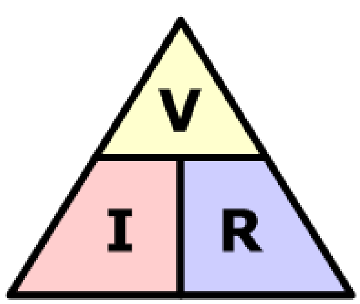
To find the Current, (I)

[I = V ÷ R]   I (amps) = V (volts) ÷ R (Ω)

To find the Resistance, (R)

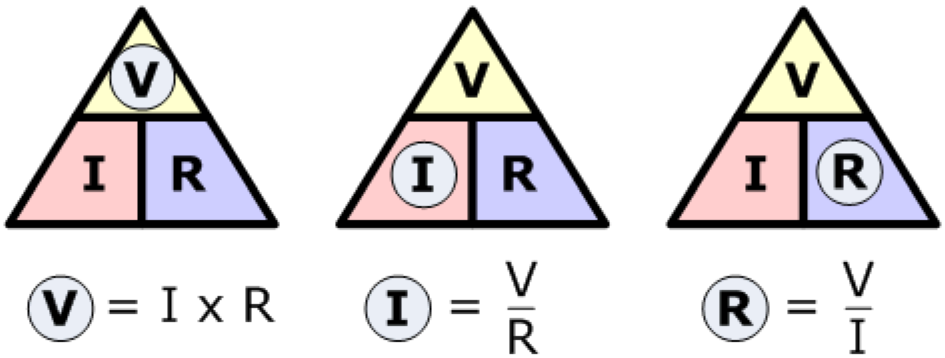
[R = V ÷ I]   R (Ω) = V (volts) ÷ I (amps)

It is sometimes easier to remember this Ohms law relationship by using pictures. Here the three quantities of V, I and R have been superimposed into a triangle (affectionately called the Ohms Law Triangle) giving voltage at the top with current and resistance below. This arrangement represents the actual position of each quantity within the Ohms law formulas.



Ohm’s Law Triangle

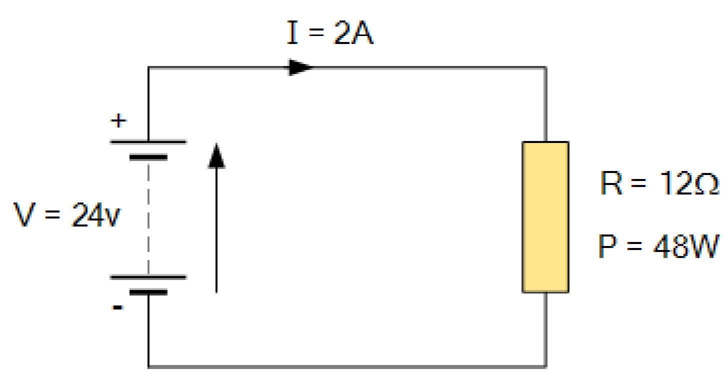
Transposing the standard Ohms Law equation above will give us the following combinations of the same equation:



Then by using Ohms Law we can see that a voltage of 1V applied to a resistor of 1Ω will cause a current of 1A to flow and the greater the resistance value, the less current that will flow for a given applied voltage. Any Electrical device or component that obeys "Ohms Law" that is, the current flowing through it is proportional to the voltage across it (I α V), such as resistors or cables, are said to be "Ohmic" in nature, and devices that do not, such as transistors or diodes, are said to be "Non-ohmic" devices.

Ohms Law Example:

For the circuit shown below find the Voltage (V), the Current (I), the Resistance (R) and the Power (P).



Voltage [V = I x R] = 2 x 12Ω = 24V

Current [I = V ÷ R] = 24 ÷ 12Ω = 2A

Resistance [R = V ÷ I] = 24 ÷ 2 = 12 Ω

Power [P = V x I] = 24 x 2 = 48W

Ohm’s Law Applications

The main applications of Ohm’s law are:

- To determine the voltage, resistance or current of an electric circuit.
- Ohm’s law is used to maintain the desired voltage drop across the electronic components.
- Ohm’s law is also used in dc ammeter and other dc shunts to divert the current.

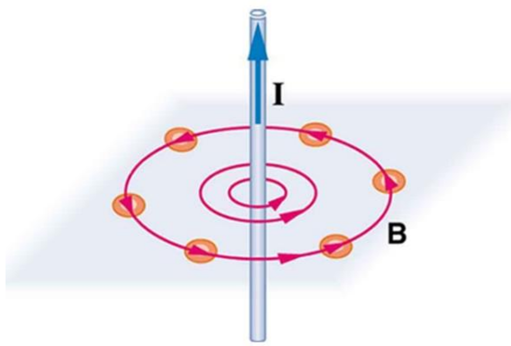
Limitations of Ohm’s Law

Following are the limitations of Ohm’s law:

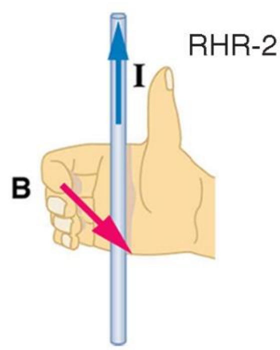
- Ohm’s law is not applicable for unilateral electrical elements like diodes and transistors as they allow the current to flow through in one direction only.
- For non-linear electrical elements with parameters like capacitance, resistance etc the voltage and current won’t be constant with respect to time making it difficult to use Ohm’s law.

Magnetic Fields

Electric current produces a magnetic field. This magnetic field can be visualized as a pattern of circular field lines surrounding a wire. One way to explore the direction of a magnetic field is with a compass, as shown by a long straight current-carrying wire in. Hall probes can determine the magnitude of the field. Another version of the right hand rule emerges from this exploration and is valid for any current segment—point the thumb in the direction of the current, and the fingers curl in the direction of the magnetic field loops created by it.



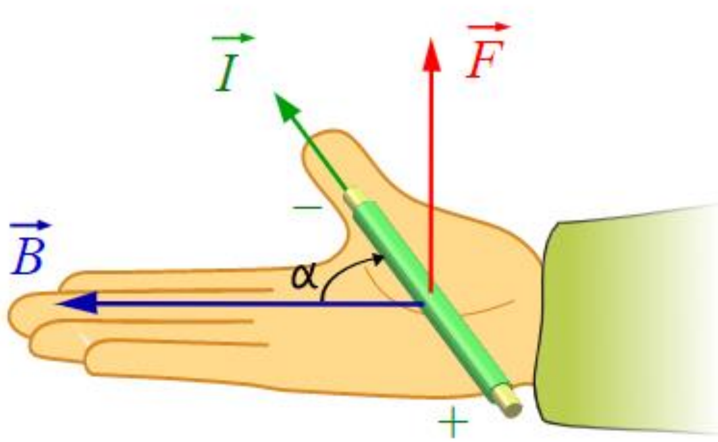
(a)



(b)

Force on a Current-Carrying Wire

The force on a current carrying wire (as in) is similar to that of a moving charge as expected since a charge carrying wire is a collection of moving charges. A current-carrying wire feels a force in the presence of a magnetic field. Consider a conductor (wire) of length **ℓ**, cross section **A**, and charge q which is due to electric current **I**. If this conductor is placed in a magnetic field of magnitude **B** which makes an angle with the velocity of charges (current) in the conductor, the force exerted on a single charge **q** is



Force on a Current-Carrying Wire: The right hand rule can be used to determine the direction of the force on a current-carrying wire placed in an external magnetic field.

$F=qvB\sin\theta$

So, for *N* charges where

$N=nlA$

the force exerted on the conductor is

$f=FN=qvBnlA\sin\theta=Bil\sin\theta$

where $i = nqvA$. The right hand rule can give you the direction of the force on the wire, as seen in the above figure. Note that the B-field in this case is the *external* field.

Magnetic Flux

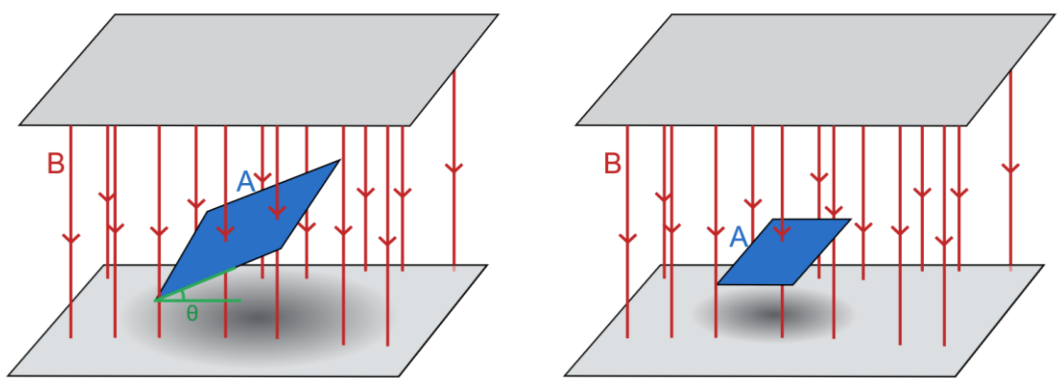
Magnetic flux is a measurement of the total magnetic field which passes through a given area. It is a useful tool for helping describe the effects of the magnetic force on something occupying a given area. The measurement of magnetic flux is tied to the particular area chosen. We can choose to make the area any size we want and orient it in any way relative to the magnetic field.

If we use the field-line picture of a magnetic field then every field line passing through the given area contributes some magnetic flux. The angle at which the field line intersects the area is also important. A field line passing through at a glancing angle will only contribute a small component of the field to the magnetic flux. When calculating the magnetic flux we include only the component of the magnetic field vector which is normal to our test area.

If we choose a simple flat surface with area A as our test area and there is an angle θ between the normal to the surface and a magnetic field vector (magnitude BBB) then the magnetic flux is,

$\Phi = BA\cos\theta$

In the case that the surface is perpendicular to the field then the angle is zero and the magnetic flux is simply BA. Figure 1 shows an example of a flat test area at two different angles to a magnetic field and the resulting magnetic flux.



The SI unit of magnetic flux is the Weber (named after German physicist and co-inventor of the telegraph Wilhelm Weber) and the unit has the symbol Wb

Faraday's Law of Induction

Faraday's law of induction is a basic law of electromagnetism that predicts how a magnetic field will interact with an electric circuit to produce an electromotive force (EMF). It is the fundamental operating principle of transformers, inductors, and many types of electrical motors, generators, and solenoids.

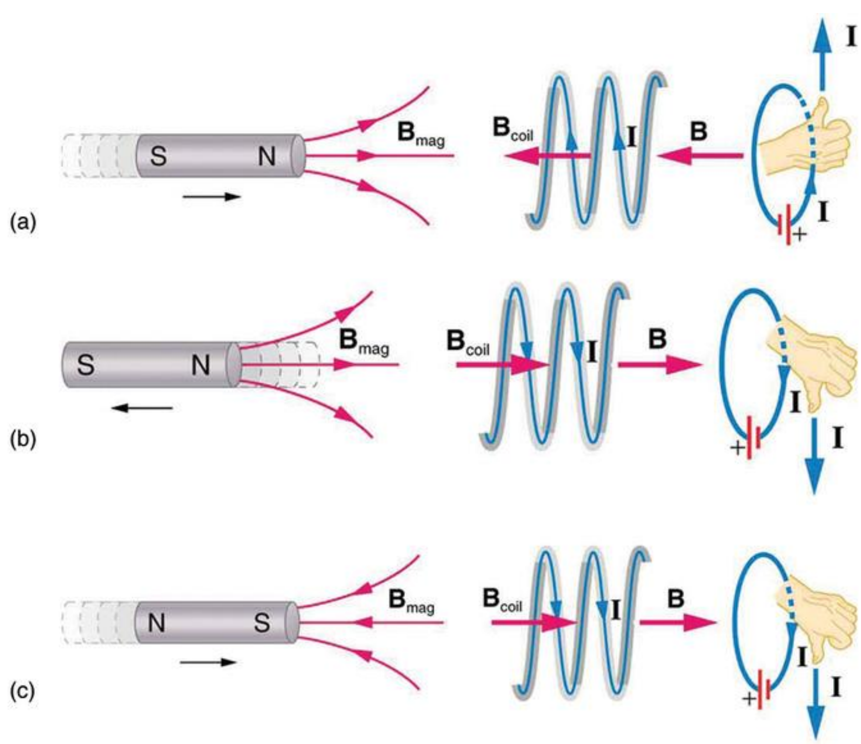
Faraday's experiments showed that the EMF induced by a change in magnetic flux depends on only a few factors. First, EMF is directly proportional to the change in flux Δ. Second, EMF is greatest when the change in time Δt is smallest that is, EMF is inversely proportional to Δt. Finally, if a coil has N turns, an EMF will be produced that is N times greater than for a single coil, so that EMF is directly proportional to N. The equation for the EMF induced by a change in magnetic flux is

$$EMF = -N\, \Delta\Phi / \Delta t$$

This relationship is known as Faraday's law of induction. The units for EMF are volts, as is usual.

Lenz' Law

The minus sign in Faraday's law of induction is very important. The minus means that the EMF creates a current I and magnetic field B that oppose the change in flux Δ this is known as Lenz' law. The direction (given by the minus sign) of the EMF is so important that it is called Lenz' law after the Russian Heinrich Lenz (1804–1865), who, like Faraday and Henry, independently investigated aspects of induction. Faraday was aware of the direction, but Lenz stated it, so he is credited for its discovery.



Lenz' Law: (a) When this bar magnet is thrust into the coil, the strength of the magnetic field increases in the coil. The current induced in the coil creates another field, in the opposite direction of the bar magnet's to oppose the increase. This is one aspect of Lenz's law—induction opposes any change in flux. (b) and (c) are two other situations. Verify for yourself that the direction of the induced Bcoil shown indeed opposes the change in flux and that the current direction shown is consistent with the right hand rule.