The structure of matter

The key ideas we will need to know are as follows:

1- Atoms are made up of electrons and nuclei;

2- The sizes of atoms are determined by the distribution of the atom's electrons;

3- The nuclei are small but contain almost all of the mass of the atom;

4- The bonding between atoms that builds molecules and crystals arises from the electrical forces between the electrons and nuclei and the sharing of electrons between different atoms.

The electrons are more complex. They are much lighter than nuclei (an electron has a mass ~1/2000 that of a neutron or proton) and, as a result, spread themselves out over a much larger volume than the nucleus does.

What matters for us here, for both electrons and nuclei, is their electrical character.

- Mass of proton (m_p) is approximately 2000 times the mass of the electron (m_e)
- More than 99% of the volume of an atom is empty space.
- Current experiments indicate that the electron has no structure, it is a true *point* particle.
- Protons and neutrons are each comprised of quarks. With the same experimental limit as the electrons, quarks also have no sub-structure.

Charge and the electric force

The basic particles of which matter is made, have properties — mass, charge, and magnetic moment. Each of these properties both creates and responds to action-at-a-distance forces.

Every charge exerts action-at-a-distance electric forces on every other charge. It's this force that holds atoms together.

The charge on the electron is in some sense opposite to the charge on a proton, in that an electron and proton at the same place will produce forces on a third charge that cancel.

We call the charge on a proton positive and the charge on the electron negative.

Since most matter is made up of equal numbers of positive and negative charges, mostly all electric forces cancel and we don't usually see their effects. But because the forces between charges depend on distance, the distribution of the positions of positive and negative charges can be important.

It is also true that for some molecules, the distribution of charge in the molecule is not uniform. One side or end might have more negative charge and another might have more positive charge. Since distance matters in electric forces, orienting a lot of such molecules together can have a significant effect.

ATOMIC NUMBER (Z)

The **atomic number (Z),** *is the number of protons found in the nucleus of an atom.* This determines the identity of the atom, an atom where Z=6 is always carbon. Changing the atomic number would change the element.

In their natural state, atoms are **neutral**. This means that they have the same number of protons and electrons. Therefore, in a neutral atom the atomic number also indicates the number of electrons.

Z = atomic number = number of protons = number of electrons in neutral atoms.

MASS NUMBER (A)

It is represented with the letter **A**.

A = number of protons + number of neutrons

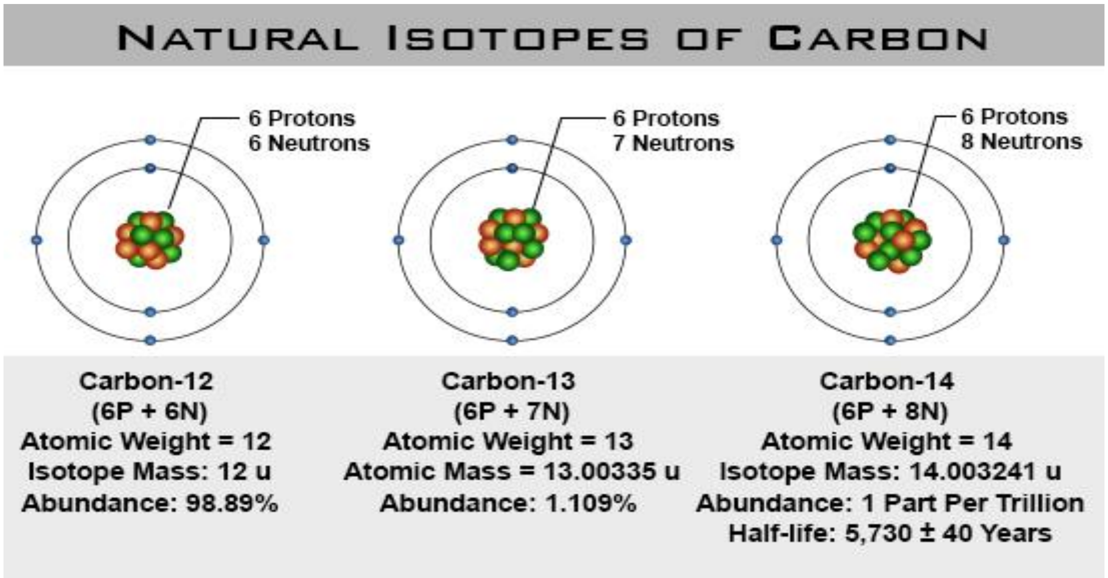
If we call the number of neutrons n, we conclude that

A = Z + n

Therefore, if we know Z (the atomic number) and A (the mass number). then we know or can work out the number of protons, neutrons and electrons in that atom.

ISOTOPES

The number of protons and electrons is always the same in all neutral atoms of a chemical element, but the number of neutrons can vary. *Atoms with the same number of protons but different numbers of neutrons are called* **isotopes**. For example: Carbon has 3 different naturally occurring isotopes:



ELECTRON SHELLS

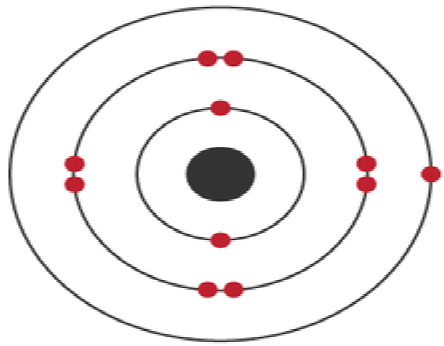
Electrons in atoms orbit in energy levels, also called electron shells, around the nucleus. The shells can only hold a certain number of electrons. The electrons in an atom occupy the lowest available energy level first. This is the shell nearest the nucleus. When this shell is full the electrons begin to occupy the next shell.

The electronic structure of an atom can be predicted from its atomic number. For example, the atomic number of sodium is 11. Sodium atoms have 11 protons and so 11 electrons:

- two electrons occupy the first shell
- eight electrons occupy the second shell
- one electron occupies the third shell

This electronic structure can be written as 2,8,1 (each comma, separates one shell from the next). This electronic structure can also be shown as a diagram. In these diagrams:

- each shell is shown as a circle
- each electron is shown as a dot or a cross



The electronic structure of an element is linked to its position on the periodic table.

Number of shells = Period number

Number of electrons in the outer shell = Group number

Total number of electrons (in a neutral atom) = number of protons (atomic number)

The electronic structure of sodium (2,8,1) shows that sodium

- is in period 3
- is in group 1
- has an atomic number of (2 + 8 + 1) = 11

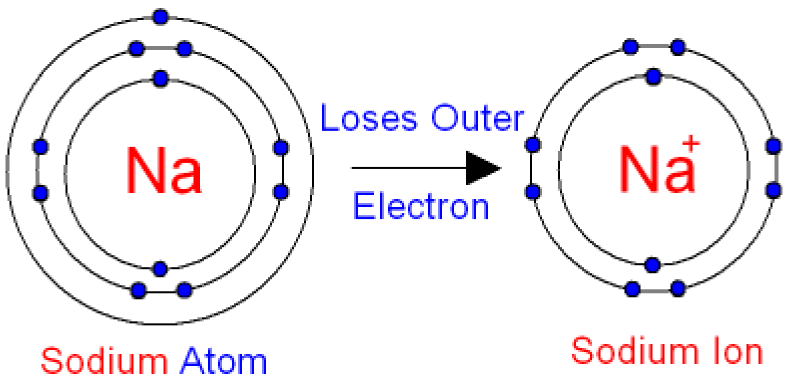
IONS

Atoms have the same number of protons and electrons, and therefore are electrically neutral. However, if an atom *loses* or *gains* electrons, the overall charge will change and will be *unbalanced*..

If the charge is not neutral, the atom has become an ***ion.*** *A positive ion is called a* ***cation****, and a negative ion is known as an* ***anion****.*

All atoms "want" to have a full outer shell to be like the Nobel gasses.. To do this they will either fill a nearly full shell or empty a shell that has only a few electrons in it.

For example sodium (Na) has 1 electron in its outer shell. It could try and get 7 more electrons to fill the shell but it is easier to lose 1 electron and have the full 2nd shell become the outer shell.



OXIDATION NUMBERS

Oxidation numbers **do not** have anything to do with oxygen. Chemists use oxidation numbers to keep track of **the number of electrons**

A positive number means that the atom has fewer electrons than protons..
A negative number means that the atom has more electrons than protons.

Calcium has a +2 charge, which means it lost two electrons.
Oxygen has a -2 charge, which means it gained two electrons

The oxidation numbers relate to the groups of the periodic table because they depend on the usual number of electrons in the outer shell that an atom has. Elements in the same group will usually have the same oxidation numbers..

Some elements, especially the transition metals can have many different oxidation numbers.

Electric Charge Definition

Electric charge can be ***defined as a fundamental property of subatomic particles that gives rise to the phenomenon of experiencing force in the presence of electric and magnetic fields***. These fields exert influence on charged particles, resulting in observable effects.

Types of Electric Charge

Electric charge comes in two main types: **positive and negative charges**.

Positive charges are associated with protons, which are subatomic particles residing in the nucleus of an atom. They are represented by the symbol “+”.

On the other hand, **negative charges** are linked to electrons, which orbit the atomic nucleus and are denoted by the symbol “-“.

Opposite charges, such as positive and negative, attract each other, while like charges, such as positive and positive or negative and negative, repel each other.

This fundamental principle is the foundation for various concepts in electromagnetism and is pivotal in understanding the interaction of charged particles.

It’s important to note that when an equal number of positive and negative charges are present, they cancel each other out, resulting in a neutral state for the object.

Measuring Electric Charge

Coloumb is the unit of electric charge. “

One coulomb *is the quantity of charge transferred in one second.”*

Mathematically, the definition of a coloumb is represented as:

$$Q = I.t$$

In the equation, Q is the electric charge, I is the electric current and t is the time.

Properties of Electric Charge

Electric charge possesses several important properties that help us understand its behaviour. Let’s explore these properties:

Additivity of Electric Charge

When charges combine, their magnitudes add up algebraically. For example, if we have a positive charge of +3 units and a negative charge of -2 units, the resulting charge would be +1 unit.

Let us consider a system of charges containing three point charges with magnitudes q_1, q_2, and q_3. In such a system, the total charge of the system can be obtained by algebraically adding the three charges.

$$Q = q_1 + q_2 + q_3$$

These charges have magnitude but no direction, are scalar quantities, and are treated like real numbers during conducting any operation. For a system containing n particles, the total charge of the system can be written as,

$$Q = q_1 + q_2 + q_3 + \cdots + q_n$$

We note that the charge can either be positive or negative and the operation takes the sign of the charge into consideration.

Conservation of Electric Charge:

In an isolated system, electric charge is conserved. *This means that the total electric charge within the system remains constant over time.* The algebraic sum of all the charges present in the system remains the same.

According to the principle of conservation of charges, the charges are neither created nor destroyed; they are only transferred from one body to the other. For example, when two objects, one has some charge and the other having no charge are made to come in contact with each other, the charge is transferred from the object possessing some charge to the object possessing no charge until the charge is equally distributed over the whole system. Here, no charge is created or lost and is only transferred from the one possessing an excess of charge to the other possessing a deficit.

If you rub a glass rod with silk, a positive charge appears on the rod. Measurement shows that a negative charge of equal magnitude appears on the silk. This suggests that rubbing does not create charge but only transfers it from one body to another, upsetting the electrical neutrality of each body during the process. . Important examples of the conservation of charge occur in the radioactive decay of nuclei, in which a nucleus transforms into (becomes) a different type of nucleus. For example, a uranium-238 nucleus (238U) transforms into a thorium- 234 nucleus (234Th) by emitting an alpha particle. Because that particle has the same makeup as a helium-4 nucleus, it has the symbol 4He.

Quantization of Electric Charge

Electric charge comes in discrete, indivisible units called elementary charges. The smallest unit of electric charge is the charge carried by an electron, which is approximately -1.6×10^{-19} coulombs. This quantization of charge implies that electric charge cannot be divided into smaller parts.

According to the principle of quantization of electric charge, all the free charges are integral multiples of a basic predefined unit, which we denote by *e*. Thus, the charge possessed by a system can be given as,

$$q = ne$$

Where n is an integer (zero, a positive or a negative number) and *e* is the basic unit of charge, that is, the charge carried by an electron or a proton. The value of *e* is 1.6×10^{-19}C.

"Every charge in the universe exerts a force on every other charge in the universe" is a bold yet true statement of physics.

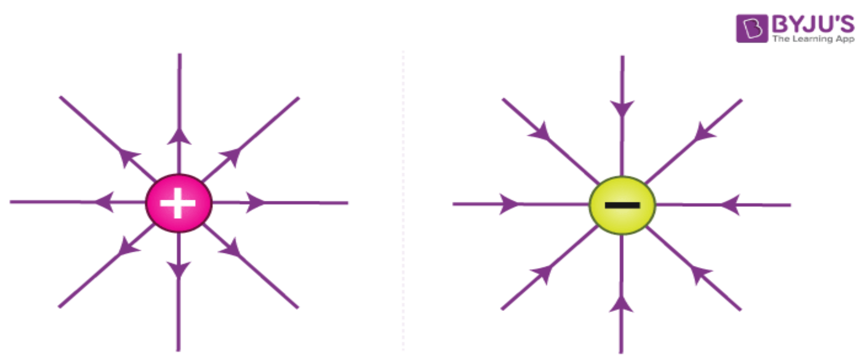
So in a simple way we can define the electrostatic field considering the force exerted by a point charge on a unit charge. In other words we can define the electric field as the *force per unit charge.*

To detect an electric field of a charge q, we can introduce a test charge q_0 and measure the force acting on it.

Note that the electric field is a vector quantity that is defined at every point in space, the value of which is dependent only upon the radial distance from q.

The test charge q_0 itself has the ability to exert an electric field around it. Hence, to prevent the influence of the test charge, we must ideally make it as small as possible.

Thus,This is the electric field of a point charge. Also, observe that it exhibits spherical symmetry since the electric field has the same magnitude on every point of an imaginary sphere centred around the charge q.



The Electric Field

Defined as *the electric force per unit charge,* is a vector field because. The direction of the field is taken to be the direction of the force it would exert on a positive test charge.

. The electric field vector E at a point in space is defined as the electric force F acting on a positive test charge q_0 placed at that point divided by the test charge:

The SI units of E are N/C. **E=F/q** **------1**

- .
- **. Relationship between F and E**
- Equation 1 can be rearranged as **F=qE**
- This equation gives us the force on a charged particle placed in an electric field.
- • This is valid for a point charge only.
-

• If test charge, q_0, is positive, the force and the field are in the same direction.

- • If test charge, q_0, is negative, the force and the field are in opposite directions.
-
- **. Electric Field Direction**
- a) If q is positive, then the force on the test charge is directed away from q.
- b) The direction of the electric field at P points is also away from the positive source charge.
- c) If q is negative, then the force on the test charge is directed toward q.

Concept of Electric Dipole

An electric dipole *is a pair of charges separated by a distance*, This pair is equal but opposite in nature of charges

What Is Field of a Electric Dipole?

A dipole is a separation of opposite electrical charges and it is quantified by an electric dipole moment. The **electric dipole moment** associated with two equal charges of opposite polarity separated by a distance, d is defined as the vector quantity having a magnitude equal to the product of the charge and the distance between the charges and having a direction from the negative to the positive charge along the line between the charges.

It is a useful concept in dielectrics and other applications in solid and liquid materials. These applications involve the energy of a dipole and the **electric field of a dipole**.

Dipole in a uniform external field

When we place an electric dipole in an uniform external field, i.e, where the electric field is uniform, then due to external force (that is, electric field), torque is produced at a point on the field which acts on the dipole.

There are molecules or charges in which the dipole moment is zero at its centre. But when they are introduced in an electric field, a dipole moment is produced.

These charges have a permanent dipole of dipole moment p in a uniform external field moment.

Now, when an electric field is introduced on these charges, a force is acted on charge +q and on -q.

A force of +qE acts on the charge +q,

and a force of -qE acts on the -q charge.

This way, the net force on the dipole becomes zero, as the electric field is uniform.

But when the electric dipole is not placed under a uniform external electric field, then what would happen to torque?

This time, evidently the net force on the dipole would not be zero.

Torque = force x distance separating forces

$$= qE \sin\Theta \times d$$

Since the dipole moment, p is the measure of separation of two charges.

Hence, $p = qd$

$$\textbf{Torque} = pE\sin\Theta = pE$$

Thus, we can define torque as a vector quantity that arises due to placing an electric dipole in an external electric field.

This torque can be maximum or minimum under different conditions.

When torque is minimum:

When the direction of the dipole moment is parallel to the external electric field then the angle between the both becomes zero.

This means, $\theta = 0^{\circ}$, And $\sin 0 = 0^{\circ}$

Hence, torque in this case would be equal to zero.

In this case, the dipole is in stable equilibrium.

When torque is maximum:

When the direction of the dipole moment is antiparallel to the external electric field that is opposite to the electric field. That is when torque is held perpendicular to the external electric field then it becomes maximum.

This means, θ= 90o,   Sin 90o= 1

Hence, the torque, in this case, would be maximum.

And the dipole would be in unstable equilibrium.

Physical Significance Of an Electric Dipole:

It gives a measure of the polarity/polarization of a system having charges.

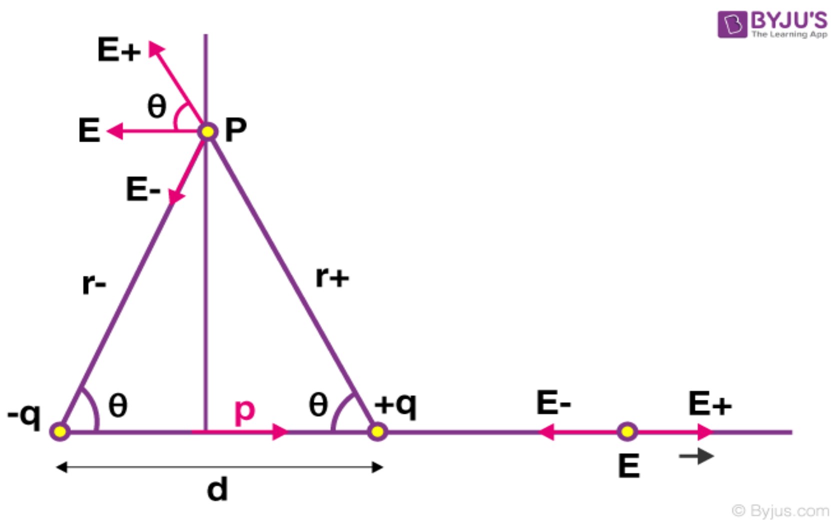
The Torque produced due to placing the dipole in an external electric field measures the tendency of a dipole to align with an external electric field.

Electric Field of a Dipole

A dipole, simply put, consists of two equal but opposite electrical charges separated by a certain distance. Combination of these charges results in an electric field which is commonly referred to as the 'electric field of a dipole'. This concept is fundamental to subjects such as electromagnetism and solid state physics.

Consider an electric dipole with charges +q and -q separated by a distance d. of simplicity, we calculate the fields along symmetry axes, i.e. a point **P** along the perpendicular bisector of the dipole at a distance r from the mid-point of the dipole and a point **Q** along the axis of the dipole at a distance r from the mid-point of the dipole.

$$E=1/4\pi\varepsilon_0 (q/(r^2)$$



The electric field due to +q at P is: $E = 1/4\pi\varepsilon_0 \, (q/(r^2-(d/2)^2)$

The electric field due to -q at P is: $E = 1/4\pi\varepsilon_0 \, (q/(r^2+(d/2)^2)$

Notice that both the fields are in the same direction, so the total electric field will be the vector sum of E_{+q} , E_{-q} : . Therefore,

$$E = E_{+q} + E_{-q}$$

Electric Potential difference

$$W = F_{ex} \, r = F_{ex} \cos\theta \, r$$

If $0 < \theta < 90$...cos θ is (+ve) then W is (+ve)

If $0 < \theta < 180$...cos θ is (+ve) then W is (−ve)

If $\theta = 90$ *between Fex* and r thenW is (0)

Relationships between Force, Field, Potential, and Energy

$$
\begin{tikzcd}[column sep=huge, row sep=huge]
\boxed{\vec{E} = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}\hat{r}} \arrow[r, shift right, "\Delta V = -\int \vec{E}\bullet d\vec{r}"'] \arrow[d, shift right, "\vec{F} = q\vec{E}"'] & \boxed{V = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}} \arrow[l, shift right, "\vec{E} = -\frac{dV}{dr}\hat{r}"'] \arrow[d, shift right, "\Delta U = q\Delta V"'] \\
\boxed{\vec{F} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}\hat{r}} \arrow[u, shift right, "\vec{E} = \frac{\vec{F}}{q}"'] \arrow[r, shift right, "\Delta U = -\int \vec{F}\bullet d\vec{r}"'] & \boxed{U = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r}} \arrow[l, shift right, "\vec{F} = -\frac{dU}{dr}\hat{r}"'] \arrow[u, shift right, "\Delta V = \frac{\Delta U}{q}"']
\end{tikzcd}
$$

Frequently Asked Questions – FAQs

Q1 **What electric charge?**

Electric Charge is the property of subatomic particles that causes it to experience a force when placed in an electric and magnetic field.

Q2 **Is electric charge a vector quantity?**

Electric charge is a scalar quantity. Apart from having a magnitude and direction, a quantity to be termed a vector should also obey the laws of vector addition, such as triangle law of vector addition and parallelogram law of vector addition; only then the quantity is said to be a vector quantity.

Q3 **State Coulomb's law.**

Coulomb's law states that the magnitude of the electrostatic force of attraction or repulsion between two point charges is directly proportional to the product of the magnitudes of charges and inversely proportional to the square of the distance between them.

Q4 **What is charging, and what are the different methods of charging?**

The process of supplying the electric charge to an object or losing the electric charge from an object is called charging.

An uncharged object can be charged in three different ways as follows:

- Charging by friction (triboelectric charging)
- Charging by conduction
- Charging by induction

Q5 **How are electric charges distributed within the atom?**

Subatomic particles carry electric charges. Electrons carry the negative charge and protons carry the positive charge in the nuclei of atoms.

Q6 **What are the types of electric charges?**

Types of electric charges are:

1. Positive (+) charge
2. Negative (-) charge

Q7 **What is electric charge?**

When a subatomic particle is subjected to an electric and magnetic field, it experiences a force due to its electric charge.

Q8 **What are the properties of electric charge?**

Properties of the electric charge are:

- (Electric charge is additive in nature.
- Conservation of electric charge.

Q9 **What is the SI unit of electric charge?**
Coulomb (C)
Q10 What is an electric dipole?
An electric dipole is defined as a couple of opposite charges q and –q separated by a distance d. By default, the direction of electric dipole in space is always from negative charge -q to positive charge q. The midpoint q and –q is called the centre of the dipole. The simplest example of an electric dipole is a pair of electric charges of two opposite signs and equal magnitude separated by distance.
Q11 **What is the SI unit of the dipole moment?**
The SI unit of dipole moment is Coulomb.meter
Q12 **Give an example of an electric dipole.**
A pair of electric charges of two opposite signs and equal magnitude separated by a distance.
Q13 **How does an atom behave as a magnetic dipole?**
The electrons in an atom revolve around the nucleus in a closed orbit. The orbit around the nucleus is equivalent to a current loop as the electrons are charged particles. The electrons revolve in anticlockwise while the current revolves in the clockwise direction. This movement of electrons creates a south pole and north pole resulting in the atom’s behaviour as a magnetic dipole.

Induced Charges

In order to charge an object, one has to alter the charge balance of positive and negative charges. There are three ways to do it: ***friction, conduction*** and ***induction***.

Charging by Friction:

The charging by friction process involves rubbing of one particle on another resulting in electrons moving from one surface to another. This method is useful for charging insulators.

Charging by Conduction:

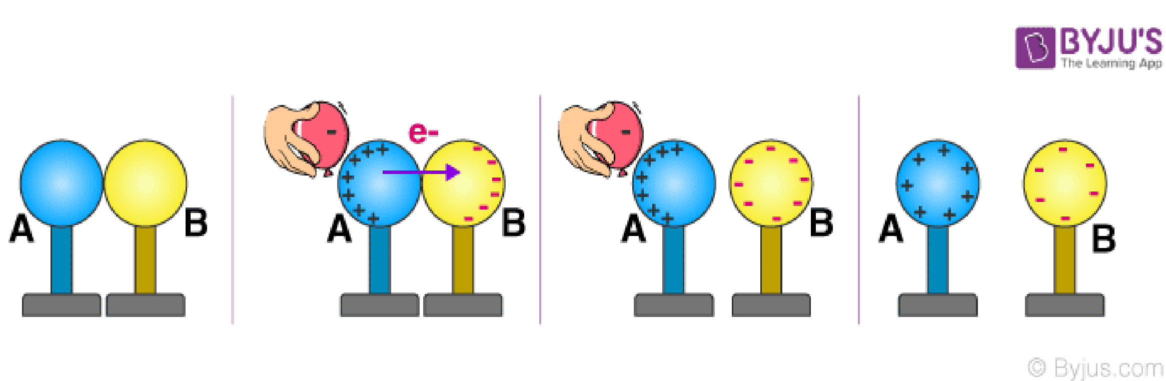
The charging by conduction process involves touching of a charged particle to a conductive material. This way, the charges are transferred from the charged material to the conductor. This method is useful for charging conductors.

Charging By Induction:

The charging by induction process is where the charged particle is held near an uncharged conductive material that is grounded on a neutrally charged material. The charge flows between two objects and the uncharged conductive material develop a charge with opposite polarity.

Charging by Induction Using a Negatively Charged Object

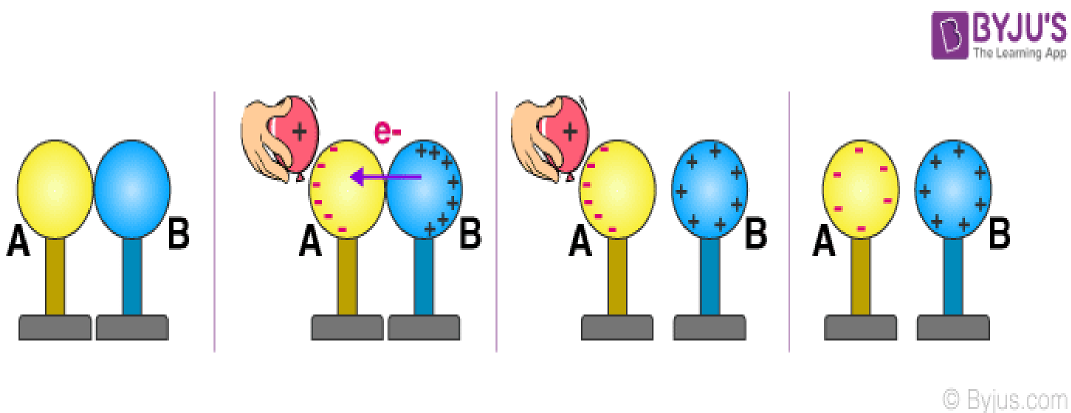
Let us consider two metal spheres A and B touching each other, as shown in the figure.



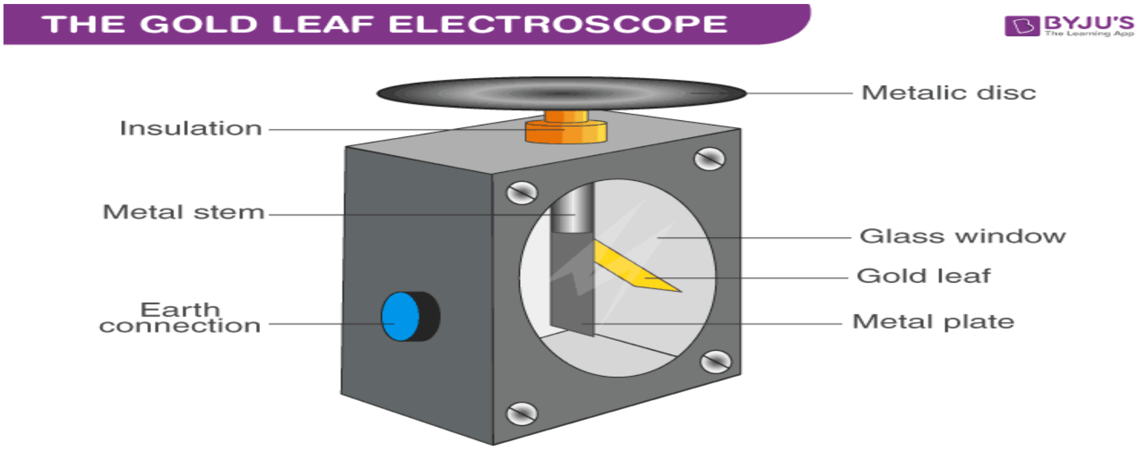
When a negatively charged balloon is brought near the sphere system, the electrons in the sphere will be forced to move away due to repulsion. The migration of electrons causes sphere A to become completely positive and sphere B to become negative The spheres are then separated using an insulating cover such as gloves or a stand as shown in the figure (avoiding direct contact with the metal). When we remove the balloon, the charge gets redistributed, spreading throughout the spheres, as shown in the figure.

Charging by Induction Using a Positively Charged Object

Taking two spheres A and B, touching each other, as shown in the figure,



When a positively charged balloon is brought near the sphere system, the electrons from sphere B will migrate towards sphere A due to the force of attraction. Now, sphere A is negatively charged and sphere B is positively charged. **The spheres are then separated using an insulating cover, a stand or gloves. When the balloon is removed, the charges in spheres A and B redistribute, spreading out evenly.**



An electroscope is an instrument that is used to detect the presence and magnitude of electric charges on a body. An electroscope is commonly used by physics teachers to demonstrate the electrostatic principles of charging and charge interactions.

The demonstration of the induction process of charging is commonly performed with an electroscope. In this demonstration, a charged particle is brought close to but not touching the electroscope. The electrons in the electroscope are induced to move due to the presence of the charged particle above the plate of the electroscope. With the charged particle still held above the plate, the electroscope is touched. At this point, electrons will flow between the electroscope and the ground, giving the electroscope an overall charge. The needle of the electroscope deflects indicating an overall charge when the charged particle is pulled away from it.

Q1**Explain charging by induction.**

Induction charging is a charging method that charges an object without actually touching the object to any other charged object. The charging by induction process is where the charged particle is held near an uncharged conductive material that is grounded on a neutrally charged material. The charge flows between two objects and the uncharged conductive material develop a charge with opposite polarity.

Q2**Explain charging by friction.**

The charging by friction process involves rubbing of one particle on another resulting in electrons moving from one surface to another. This method is useful for charging insulators.

Q3**Explain charging by conduction.**

The charging by conduction process involves touching of a charged particle to a conductive material. This way, the charges are transferred from the charged material to the conductor. This method is useful for charging conductors.

Q4**What is electromagnetic induction?**

The generation of emf in a conductor due to the rate of change of current in a nearby conductor without any electrical connection.

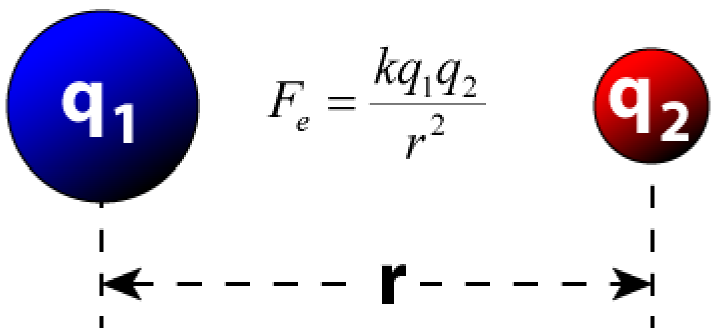
Q5**What is a charge transfer complex?**

A charge transfer complex also called the electron donor-acceptor complex can be defined as an association of two or more molecules or of different parts of a large molecule, in which a fraction of electric charge is transferred between the molecular entities. Charge transfer often occurs in inorganic ligand chemistry involving metals.

Coulomb's Law

Coulomb's Law gives an idea about the force between two point charges. Coulomb**,** measured the force between two point charges and he came up with the theory *that the force is directly proportional to the product of charges (magnitudes only)b and inversely proportional to the square of the distance between the charges.*

Let's say that there are two charges q_1 and q_2. The distance between the charges is 'r', and the force of attraction/repulsion between them is 'F'.



Then the force between them

$$F \propto q_1q_2$$

$$\text{Or, } F \propto 1/r^2$$

$$F = k\, q_1q_2/ r^2$$

where k is proportionality constant and equals to $1/4\ \pi\ \varepsilon_0$. Here, ε_0 is the epsilon naught and it signifies permittivity of a vacuum. The value of k comes 9×10^9 Nm^2/C^2 when we take the S.I unit of value of ε_0 is $8.854 \times 10^{-12}\ C^2\ N^{-1}\ m^{-2}$.

This means charges of same sign will push each other with repulsive forces while charges with opposite signs will pull each other with attractive force.

Question: Two charges 1 C and – 3 C are kept at a distance of 3 m. Find the force of attraction between them.

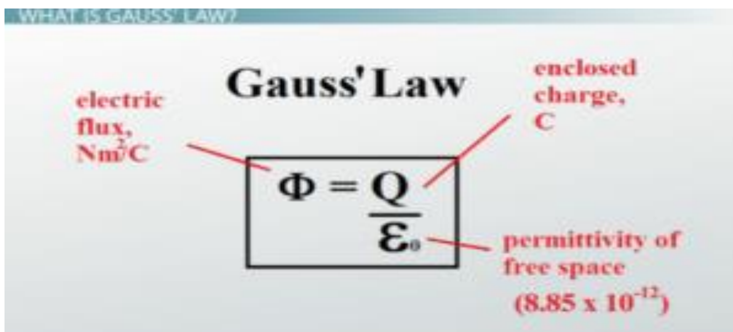
Solution: We have q_1 = 1C, q_2 = – 3C and r = 3m. Then using Coulomb's Law and substituting above values we get

$$F = k\, q_1 q_2 / r^2$$

$$\text{Or, } F = 9 \times 10^9 \times 1 \times 3 / 3^2$$

$$F = 3 \times 10^9 \text{ \underline{Newton}}$$

Gauss's law



Gauss's law states that the *net flux of an electric field in a closed surface is directly proportional to the enclosed electric charge.*

The electric flux is defined *as the electric field passing through a given area multiplied by the area of the surface in a plane perpendicular to the field.*

Yet another statement of Gauss's law states that *the net flux of a given electric field through a given surface, divided by the enclosed charge should be equal to a constant.*

Usually, a positive electric charge is supposed to generate a positive electric field.

Gauss Law Equation

Gauss's law in integral form is given below:

$$\int \mathbf{E}\cdot d\mathbf{A}=Q/\varepsilon_0 \quad \ldots\ldots (1)$$

Where,

- **E** is the electric field vector
- Q is the enclosed electric charge
- ε_0 is the electric permittivity of free space
- **A** is the outward pointing normal area vector

Flux is a measure of the strength of a field passing through a surface. Electric flux is defined as

$$\Phi=\int \mathbf{E}\cdot d\mathbf{A} \quad \ldots. (2)$$

We can understand the electric field as flux density.

Gauss's law implies that the net electric flux through any given closed surface is zero unless the volume bounded by that surface contains a net charge.

In matters, the dielectric permittivity may not be equal to the permittivity of free-space (i.e. $\varepsilon \neq \varepsilon_0$). In the matter, the density of electric charges can be separated into a "free" charge density (ρ_f) and a "bounded" charge density (ρ_b), such that:

$$P = \rho_f + \rho_b$$

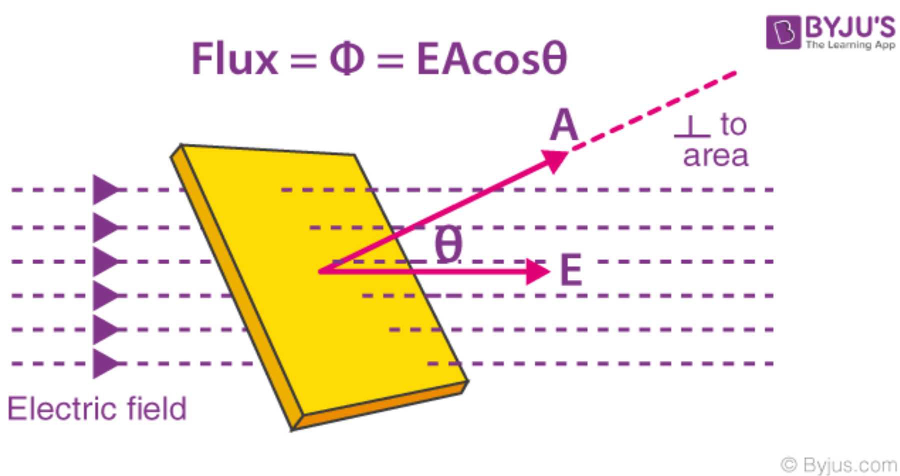
Question: There are three charges q_1, q_2, and q_3 having charge 6 C, 5 C and 3 C enclosed in a surface. Find the total flux enclosed by the surface.

Answer: Total charge Q, Q = q1 + q2 + q3
= 6 C + 5 C + 3 C
= 14 C

The total flux, $\phi = Q/\epsilon_0$
$\phi = 14C / (8.854\times10^{-12}\ F/m)$
$\phi = 1.584\ Nm^2/C$

What is Electric Flux?

The total number of electric field lines passing a given area in a unit of time is defined as the electric flux. The electric field lines of magnitude E pass through a plane of area A that is kept at an angle θ to the direction of the electric field.



if the plane is normal to the flow of the electric field, the total flux is given as:

$$\Phi = EA$$

When the same plane is tilted at an angle θ, the projected area is given as $A\cos\theta$, and the total flux through this surface is given as:

$$\Phi = EA\cos\theta$$

Where,

- E is the magnitude of the electric field
- A is the area of the surface through which the electric flux is to be calculated
- θ is the angle made by the plane and the axis parallel to the direction of flow of the electric field
-

Properties of Electric Flux

Electric flux is a scalar quantity since it is a dot product.

It is positive when the electric lines of force move away from the surface.

It is negative when the electric lines of force move towards the surface.

Flux is generally related to the lines of force passing through a region. These lines of force depend on factors like electric field strength, surface area, and surface orientation related to the lines of force.

Electric flux lines are the lines of force around a charge, and they have the following properties:

- Flux lines start with positive charges and terminate with negative charges.
- The flux lines determine the electric field’s intensity.
- Flux lines are parallel to each other, and they generally enter or exit a charged surface.

Applications of Electric Flux

- Electric flux application helps calculate the electric field for a given charge distribution enclosed by a closed surface.
- The electric flux concept is used in electric motors, inductors, and mechanical electric generators through current and electricity.

- Electric flux is used in photocopying machines and cleaning appliances like household air purifiers and industrial electrostatic precipitators.

Solved Examples for You

Question: An electric field of 500 V/m makes an angle of 30.00 with the surface vector. It has a magnitude of 0.500 m2. Find the electric flux that passes through the surface.

Solution: The electric flux which is passing through the surface is given by the equation as:

$\Phi_E = E.A = EA \cos\theta = (500\ V/m)\ (0.500\ m^2) \cos 30 = 217\ V\ m$

Question: Consider a uniform electric field $E = 3 \times 10^3 \hat{i}$ N/C. What is the flux of this field through a square of 10 cm on a side whose plane is parallel to the yz plane?

A. 30 Nm^2 / C

B. 40 Nm^2 / C

C. 50 Nm^2 / C

D. 60 Nm^2 / C

Solution: The flux of an electric field is given by,

$\phi = EA \Rightarrow \phi = 3 \times 10^3 \times 0.1 \times 0.1 \Rightarrow \phi = 30\ Nm^2/C$

Therefore, the flux of the field through a square of 10 cm on a side whose plane is parallel to the yz plane is 30 Nm^2/C

Question 2

A short electric dipole has dipole moment of $4x10^{-9}$ Cm. Find the following

(a) Electric Potential at a point distanct .3m from center of the dipole on the axial line

(b) Electric Potential at a point distanct 1 m from center of the dipole on the equatorial line

(c) Electric Potential at a point distanct .3m from center of the dipole on an line making at angle 30° with the dipole axis

Solution

Given

$p=4\times10^{-9}$ Cm

Potential of dipole is given as $V=1/4\pi\epsilon_0 \ (p\cos\theta/r^2)$

(a) $\theta=0^0$, r=.3m

$V=1/4\pi\epsilon_0 \ p/r^2$ =400V

(b) $\theta=90^0$, r=1m , V=0

(c) $\theta=30^0$, r=.3m ,$V=200\sqrt{\boxed{3}}$

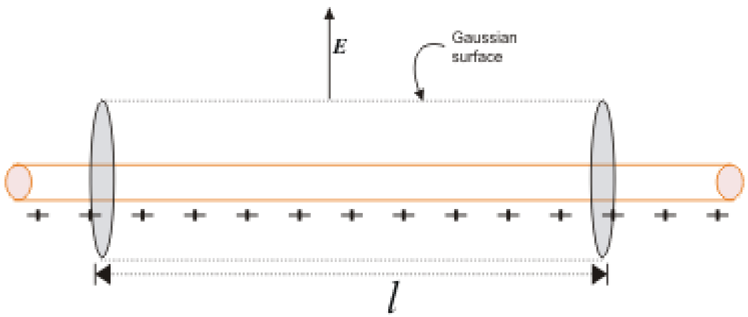
Application of Gauss Law

One should make use of symmetry to make problems easier. We must also remember that it is not necessary for the Gaussian surface to coincide with the real surface. It can be inside or outside the Gaussian surface.

Electric Field due to Infinite Wire

Let us consider an infinitely long wire with linear charge density **λ** and length L. To calculate electric field, we assume a cylindrical Gaussian surface. As the electric field E is radial in direction, the flux through the end of the cylindrical surface will be zero.

This is because the electric field and area vector are perpendicular to each other. As the electric field is perpendicular to every point of the curved surface, we can say that its magnitude will be constant.



The surface area of the curved cylindrical surface is 2πrl.

The electric flux (ϕ) through the curve is =EA =E × 2πrl

According to Gauss's Law

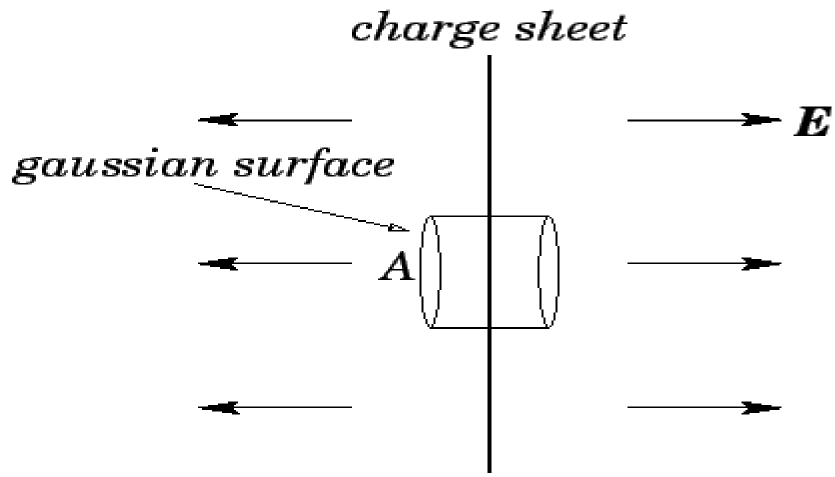
$$\Phi = \frac{q}{\varepsilon_0}$$

$$E \times 2\pi rl = \frac{\lambda l}{\varepsilon_0}$$

$$E = \frac{\lambda}{2\pi\varepsilon_0 r}$$

Electric Field due to Infinite Plate Sheet

Let us consider an infinite plane sheet, with surface charge density σ and cross-sectional area A. The position of the infinite plane sheet is as below:



The direction of the electric field due to an infinite charge sheet is perpendicular to the plane of the sheet. Let us consider a cylindrical Gaussian surface, whose axis is normal to the plane of the sheet. We can evaluate the electric field **E** from Gauss's Law as according to the law:

$$\Phi = \frac{q}{\varepsilon_0}$$

From a continuous charge distribution charge q will be = σA.

Talking about net electric flux, we will consider electric flux only from the two ends of the assumed Gaussian surface. We can attribute it to the fact that the curved surface area and an electric field are normal to each other, thereby producing zero electric flux. So the net electric flux is

$$\Phi = EA - (-EA) = 2EA$$

Then, we can write

$$2EA = \frac{\sigma A}{\varepsilon_0}$$

$$E = \frac{\sigma}{2\varepsilon_0}$$

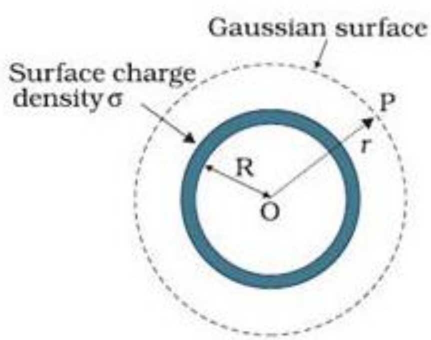
Electric Field due to Thin Spherical Shell

Let us consider a thin spherical shell of surface charge density σ and radius "R

we can evaluate the electric field due to the spherical shell in two different positions:

- Electric field outside the spherical shell
- Electric field inside the spherical shell

Let us look at these two cases in greater detail.



Electric Field outside the Spherical Shell

To find electric field outside the spherical shell, we take a point P outside the shell at a distance r from the centre of the spherical shell. By symmetry, we take Gaussian spherical surface with radius r and centre O.

The Gaussian surface will pass through P, and experience a constant electric field **E** all around as all points are equally distanced "r'' from the center of the sphere. Then, according to Gauss's Law:

$$\Phi = \frac{q}{\varepsilon_0}$$

The enclosed charge inside the Gaussian surface q will be = $\sigma A = \sigma \times 4\pi R^2$.

The total electric flux through the Gaussian surface will be

$$\Phi = E \times 4\pi r^2$$

Then by Gauss's Law, we can write

$$E \times 4\pi r^2 = \sigma \times \frac{4\pi R^3}{\varepsilon_0}$$

$$E = \frac{\sigma R^2}{\varepsilon_0 \; r^2}$$

Electric Field inside the Spherical Shell

To evaluate electric field inside the spherical shell, let's take a point P inside the spherical shell. By symmetry, we again take a spherical Gaussian surface passing through P, centered at O and with radius r. Now according to Gauss's Law

$$\Phi = \frac{q}{\varepsilon_0}$$

The net electric flux will be $E \times 4\pi r^2$.

Solved Example for You

Question: Why is there no electric field inside a spherical shell?

Solution: The enclosed charge q will be zero, as we know that surface charge density is dispersed outside the surface, therefore there is no charge inside the spherical shell. Therefore, E = 0

Conductors and Insulators

What are Conductors?

Conductors have free electrons on its surface which allow current to pass through easily. They conduct electricity because they allow electrons to flow easily inside them from atom to atom. Also, conductors allow the transmission of heat or light from one source to another. Metals, humans, earth, and animals are all conductors. This is the reason we get electric shocks! Moreover, the human body is a good conductor.

Examples of Conductors

- Material such as silver is the best conductor of electricity. But, it is costly and so, we don't use silver in industries and transmission of electricity.
- Copper, Brass, Steel, Gold, and Aluminium are good conductors of electricity. We use them in electric circuits and systems in the form of wires.
- Mercury is an excellent liquid conductor. Thus, this material finds use in many instruments.
- Gases are not good conductors of electricity because the atoms are quite far away. Thus, they are unable to conduct electrons

Applications of Conductors

Conductors are quite useful in many ways. They find use in many real-life applications. For example,

- Mercury is a common material in thermometer to check the temperature of the body.
- Aluminium finds its use in making foils to store food. It is also used in the production of fry pans to store heat quickly.
- Iron is a common material used in vehicle engine manufacturing to conduct heat.
- The plate of iron is made up of steel to absorb heat briskly.

- Conductors find their use in car radiators to eradicate heat away from the engine.

Insulators

Insulators are the materials or substances which resist or don't allow the current to flow through them. In general, they are solid in nature.

Wood, cloth, glass, mica, and quartz are some good examples of insulators. Also, insulators are protectors. They give protection against heat, sound and of course passage of electricity. Furthermore, insulators don't have any free electrons. It is the main reason why they don't conduct electricity.

Examples of Insulators

- Glass is the best insulator as it has the highest resistivity.
- Plastic is a good insulator and it finds its use in making a number of things.
- Rubber is a common material used in making tyres, fire-resistant clothes and slippers. This is because it is a very good insulator.

Applications of Insulators

As insulators resist the flow of electron, they find worldwide applications. Some of the common uses include:

- Thermal insulators, disallow heat to move from one place to another. Hence, we use them in making thermoplastic bottles. They are also used in fireproofing ceilings and walls.
- Sound insulators help in controlling noise level, as they are good in absorbance of sound. Thus, we use them in buildings and conference halls to make them noise-free.
- Electrical insulators hinder the flow of electron or passage of current through them. So, we use them extensively in circuit boards and high-voltage systems. They are also used in coating electric wire and cables

- **Difference between Conductors and Insulators**
- Let us look at the basic difference between conductors and insulators in a nutshell.

Conductors	**Insulators**
A conductor allows current to flow easily through it.	Insulators don’t allow current to flow through it.
Electric charge exists on the surface of conductors	Electric charges are absent in insulator.
Conductors don’t store energy when kept in a magnetic field	Insulators store energy when kept in a magnetic field
Thermal conductivity (heat allowance) of a conductor is very high	Thermal conductivity of an insulator is very low
The resistance of a conductor is very low	The resistance of insulator is very high
Copper, Aluminium, and Mercury are some conductors	Wood, paper and ceramic are some insulators
Conductors are used in making electrical equipment.	Insulators are used in insulating electrical equipment for safety purpose

Ohm's law

Ohm's law states that the current through a conductor between two points is directly proportional to the potential difference across the two points. Introducing the constant of proportionality, the resistance,

$$I=V/R$$

where *I* is the current through the conductor in units of amperes, *V* is the potential difference measured *across* the conductor in units of volts, and *R* is the resistance of the conductor in units of ohms. More specifically, Ohm's law states that the *R* in this relation is constant, independent of the current.

Electric current: • Net charge flowing through given cross-sectional area per unit time. •

$$I = dQ\ dt\ .$$

SI unit: 1C/s = 1A (one Ampere)

Types of Current

The current can be divided into two types.

Direct Current:

- Direct current travels in 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. The more the current in a conductor, the higher will be the current density.

The formula for Current Density is given as,

$$\mathbf{J = I / A}$$

Where,

I = current flowing through the conductor in Amperes

A = cross-sectional area in m^2.

Current density is expressed in A/m^2.

Solved Problem on Current Density

Example 1: **Determine the current density when 40 amperes of current is flowing through the battery in a given area of 10 m^2.**

Solution:

The current density formula is given by,

$J = I / A = 40 / 10 = 4\ A/m^2$.

Example 2: If the current density is 4 A/m^2 and the current through the conductor is 24 A. Find the cross-sectional area.

Solution:

Since, $J = I/A$

$A = I/J = 24/4 = 6\ m^2$

Asked Questions –

Q1: What is current?

We can define current as the flow of electrically charged particles travelling. Electric current is represented as I.

Q2: What are the types of current?

The following are the types of electric current:

- Direct Current
- Alternating Current

Q3: What is meant by current density?

The amount of current travelling per unit cross-section area is known as current density and expressed in amperes per square metre.

Q4 :Give the formula for the current density.

The formula for current density is J = I/A.

Q5: Which type of current is generated by an electrochemical cell?

Direct current is generated by an electrochemical cell.

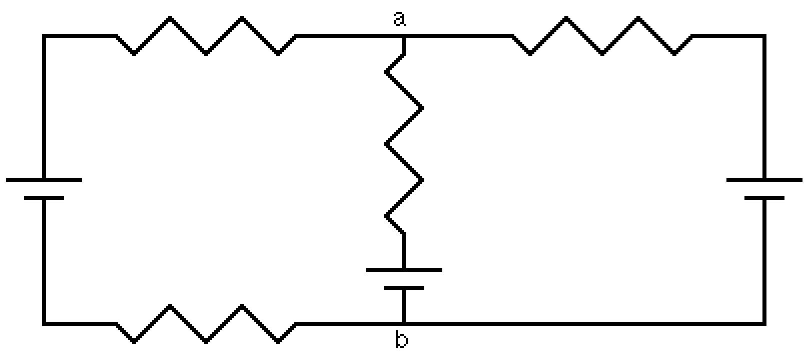
Multi-loop Circuits and Kirchoff's Rules

It is helpful to define two terms, junction and branch.

A junction is a point where at least three circuit paths meet.

A branch is a path connecting two junctions.

In the circuit below, there are two junctions, labeled a and b. There are three branches: these are the three paths from a to b.



Multi-loop circuits

In a circuit involving one battery and a number of resistors in series and/or parallel, the resistors can generally be reduced to a single equivalent resistor. With more than one battery, the situation is trickier. If all the batteries are part of one branch they can be combined into a single equivalent battery. Generally, the batteries will be part of different branches, and another method has to be used to analyze the circuit to find the current in each branch. Circuits like this are known as multi-loop circuits.

Finding the current in all branches of a multi-loop circuit (or the emf of a battery or the value of a resistor) is done by following guidelines known as Kirchoff's rules. These guidelines also apply to very simple circuits.

K**irchoff's first rule** : the junction rule. The sum of the currents coming in to a junction is equal to the sum leaving the junction. (Basically this is conservation of charge)

Kirchoff's second rule : the loop rule. The sum of all the potential differences around a complete loop is equal to zero. (Conservation of energy)

The branch current method

To analyze a circuit using the branch-current method involves three steps:

1. Label the current and the current direction in each branch. Sometimes it's hard to tell which is the correct direction for the current in a particular loop. That does NOT matter. Simply pick a direction. If you guess wrong, youšll get a negative value. The value is correct, and the negative sign means that the current direction is opposite to the way you guessed. You should use the negative sign in your calculations, however.

2. Use Kirchoff's first rule to write down current equations for each junction that gives you a different equation. For a circuit with two inner loops and two junctions, one current equation is enough because both junctions give you the same equation.

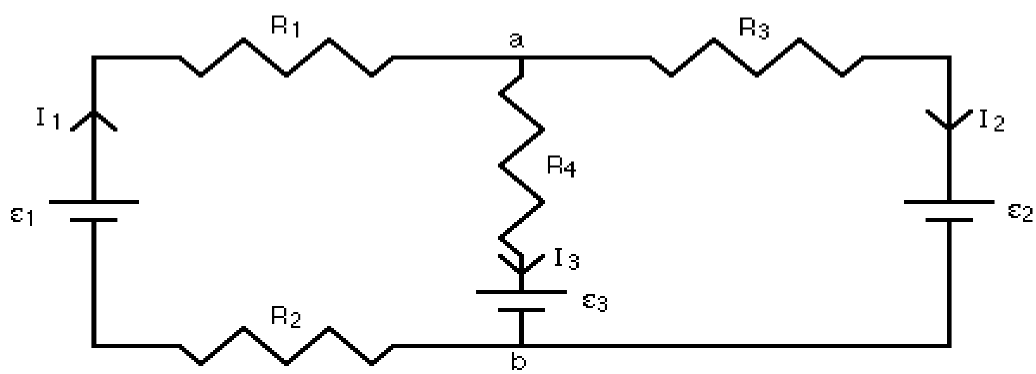
3. Use Kirchoff's second rule to write down loop equations for as many loops as it takes to include each branch at least once. To write down a loop equation, you choose a starting point, and then walk around the loop in one direction until you get back to the starting point. As you cross batteries and resistors, write down each voltage change. Add these voltage gains and losses up and set them equal to zero.

When you cross a battery from the - side to the + side, that's a positive change. Going the other way gives you a drop in potential, so that's a negative change.

When you cross a resistor in the same direction as the current, that's also a drop in potential so it's a negative change in potential. Crossing a resistor in the opposite direction as the current gives you a positive change in potential.

An example

Running through an example should help clarify how Kirchoff's rules are used. Consider the circuit below:



The battery emf's are : $\varepsilon_1 = 19$ V $\quad \varepsilon_2 = 6$ V $\quad \varepsilon_3 = 2$ V

The resistors are : $R_1 = 6\ \Omega \quad R_2 = 4\ \Omega \quad R_3 = 4\ \Omega \quad R_4 = 1\ \Omega$

Step 1 of the branch current method has already been done. The currents have been labeled in each branch of the circuit, and the directions are shown with arrows. Again, you don't have to be sure of these directions at this point. Simply choose directions, and if any of the currents come out to have negative signs, all it means is that the direction of that current is opposite to the way you've shown on your diagram.

Applying step 2 of the branch current method means looking at the junctions, and writing down a current equation. At junction a, the total current coming in to the junction equals the total current flowing away. This gives:

$$\text{at junction a} : I_1 = I_2 + I_3$$

If we applied the junction rule at junction b, we'd get the same equation. So, applying the junction rule at one of the junctions is all we need to do. In some cases you will need to get equations from more than one junction, but you'll never need to get an equation for every junction.

There are three unknowns, the three currents, so we need to have three equations. One came from the junction rule; the other two come from going to step 3 and applying the loop rule.

There are three loops to use in this circuit: the inside loop on the left, the inside loop on the right, and the loop that goes all the way around the outside.

We just need to write down loop equations until each branch has been used at least once, though, so using any two of the three loops in this case is sufficient.

When applying the loop equation, the first step is to choose a starting point on one loop. Then walk around the loop, in either direction, and write down the change in potential when you go through a battery or resistor. When the potential increases, the change is positive; when the potential decreases, the change is negative. When you get back to your starting point, add up all the potential changes and set this sum equal to zero, because the net change should be zero when you get back to where you started.

When you pass through a battery from minus to plus, that's a positive change in potential, equal to the emf of the battery. If you go through from plus to minus, the change in potential is equal to minus the emf of the battery.

Current flows from high to low potential through a resistor. If you pass through a resistor in the same direction as the current, the potential, given by IR, will decrease, so it will have a minus sign. If you go through a resistor opposite to the direction of the current, you're going from lower to higher potential, and the IR change in potential has a plus sign.

Keeping all this in mind, let's write down the loop equation for the inside loop on the left side. Picking a starting point as the bottom left corner, and moving clockwise around the loop gives:

$$+\varepsilon_1 - I_1R_1 - I_3R_4 - \varepsilon_3 - I_1R_2 = 0$$

Make sure you match the current to the resistor; there is one current for each branch, and a loop has at least two branches in it.

The inner loop on the right side can be used to get the second loop equation. Starting in the bottom right corner and going counter-clockwise gives:

$$+\varepsilon_2 + I_2R_3 - I_3R_4 - \varepsilon_3 = 0$$

Plugging in the values for the resistances and battery emf's gives, for the three equations:

$I_1 = I_2 + I_3$ (equation 1)

$+19 - 6I_1 - I_3 - 2 - 4I_1 = 0$ so $10I_1 + I_3 = 17$ (equation 2)

$+6 + 4I_2 - I_3 - 2 = 0$ so $4I_2 - I_3 = -4$ (equation 3)

The simplest way to solve this is to look at which variable shows up in both loop equations (equations 2 and 3), solve for that variable in equation 1, and substitute it in in equations 2 and 3.

Rearranging equation 1 gives:

$$I_3 = I_1 - I_2$$

Substituting this into equation 2 gives:

$10I_1 + (I_1 - I_2) = 17$ so $11I_1 - I_2 = 17$ (equation 4)

Making the same substitution into equation 3 gives:

$4I_2 - (I_1 - I_2) = -4$ so $-I_1 + 5I_2 = -4$ (equation 5)

This set of two equations in two unknowns can be reduced to one equation in one unknown by multiplying equation 4 by 5 and adding the result to equation 5.

5 x equation 4: $55I_1 - 5I_2 = 85$

+ equation 5: $-I_1 + 5I_2 = -4$

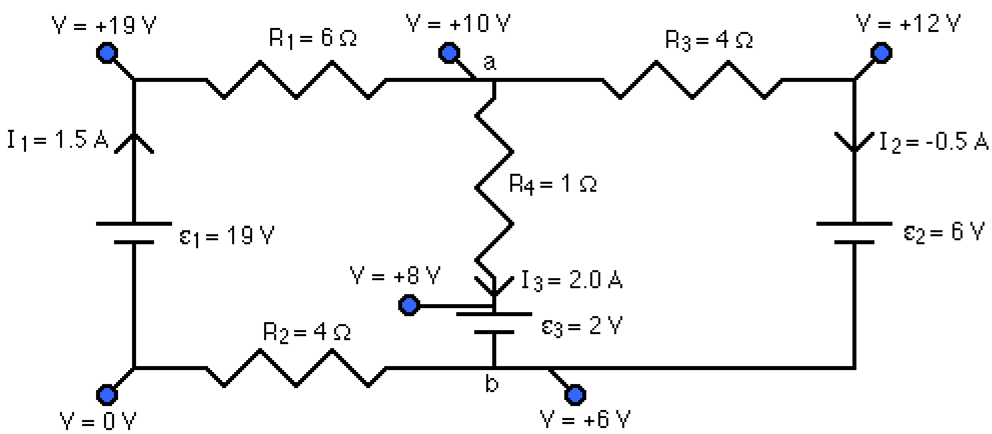
$54I_1 = 81$ so $I_1 = 1.5$ A

Substituting this into equation 5 gives:

$$I_2 = (-4 + 1.5) / 5 = -0.5 \text{ A}$$

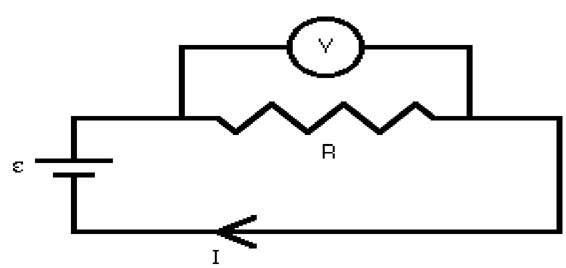
The negative sign means that the current is 0.5 A in the direction opposite to that shown on the diagram. Solving for the current in the middle branch from equation 1 gives:

$$I_3 = 1.5 - (-0.5) = 2.0 \text{ A}$$



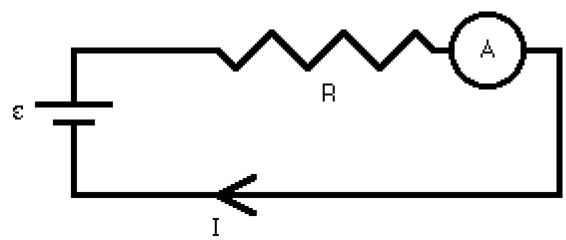
One final note: you can use this method of circuit analysis to solve for more things than just the current. If one or more of the currents was known (maybe the circuit has an ammeter or two, measuring the current magnitude and direction in one or two branches) then an unknown battery emf or an unknown resistance could be found instead.

Voltmeters



Resistors in parallel have the same voltage across them, so if you want to measure the voltage across a circuit element like a resistor, you place the voltmeter in parallel with the resistor. To prevent the voltmeter from changing the current in the circuit (and therefore the voltage across the resistor), the voltmeter must have a resistance much larger than the resistor's. With a large voltmeter resistance, hardly any of the current in the circuit makes a detour through the meter.

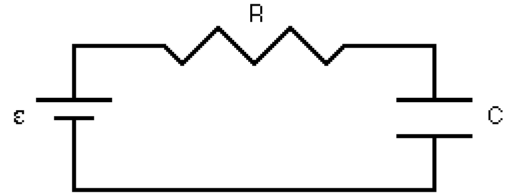
Ammeters



Remember that resistors in series have the same current flowing through them. An ammeter, then, must be placed in series with a resistor to measure the current through the resistor. On a circuit diagram, an ammeter is shown as an A in a circle. Again, the ammeter acts as a resistor, so to minimize its impact on the circuit it must have a small resistance relative to the resistance of the resistor whose current is being measured.

RC Circuits

Resistors are relatively simple circuit elements. When a resistor or a set of resistors is connected to a voltage source, the current is constant. If a capacitor is added to the circuit, the situation changes. In a simple series circuit, with a battery, resistor, and capacitor in series, the current will follow an exponential decay. The time it takes to decay is determined by the resistance (R) and capacitance (C) in the circuit.



A capacitor is a device for storing charge. In some sense, a capacitor acts like a temporary battery. When a capacitor is connected through a resistor to a battery, charge from the battery is stored in the capacitor. This causes a potential difference to build up across the capacitor, which opposes the potential difference of the battery. As this potential difference builds, the current in the circuit decreases.

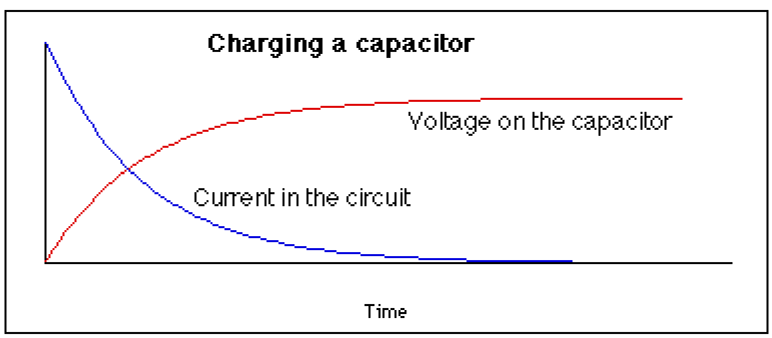
If the capacitor is connected to a battery with a voltage of Vo, the voltage across the capacitor varies with time according to the equation:

$$V = V_0 [1 - e^{-t/RC}]$$

The current in the circuit varies with time according to the equation:

$$I = I_0 e^{-t/RC}$$

Graphs of voltage and current as a function of time while the capacitor charges are shown below.

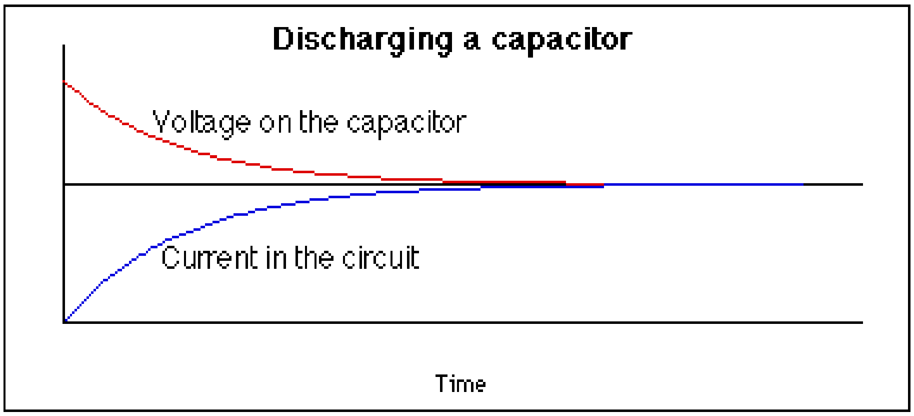


The product of the resistance and capacitance, RC, in the circuit is known as the time constant. This is a measure of how fast the capacitor will charge or discharge.

After charging a capacitor with a battery, the battery can be removed and the capacitor can be used to supply current to the circuit. In this case, the current obeys the same equation as above, decaying away exponentially, and the voltage across the capacitor will vary as:

$$V = V_0 e^{-t/RC}$$

Graphs of the voltage and current while the capacitor discharges are shown here. The current is shown negative because it is opposite in direction to the current when the capacitor charges.



What Is Electromotive Force?

Electromotive force is defined as *the electric potential produced by either an electrochemical cell or by changing the magnetic field.* **Symbol for Electromotive Force ,** is ε.

What Is Electromotive Force Formula?

Following is the formula for electromotive force:

$$\varepsilon = V + Ir$$

Where,

- V is the voltage of the cell, I is the current across the circuit, r is the internal resistance of the cell, ε is the electromotive force

What Is the Unit of EMF?

The **unit for electromotive force is Volt.**

Dimension of Electromotive Force :

EMF is given as the ratio of work done on a unit charge

Difference between Electromotive Force and Potential Difference

Electromotive Force	**Potential Difference**
EMF is defined as the work done on a unit charge	Potential difference is defined as the energy which is dissipated as the unit charge pass through the components
EMF remains constant	Potential difference is not constant
EMF is independent of circuit resistance	The potential difference depends on the resistance between the two points during the measurement
Due to EMF, electric, magnetic, and the gravitational field is caused	Due to the potential difference, the only electric field is induced
It is represented by E	It is represented by V

Definition of Capacitance

The **capacitance**, *C*, of a capacitor is defined the capacitance of a capacitor is the amount of charge the capacitor can store per unit of potential difference.

The SI unit of capacitance is the **farad** (F).

The farad is a large unit, typically you will see microfarads (mF) and picofarads (pF).

Capacitance will always be a positive quantity .The capacitance of a given capacitor is constant.

The capacitance is a measure of the capacitor's ability to store charge.

Makeup of a Capacitor

A capacitor consists of two conductors.

- These conductors are called plates.
- When the conductor is charged, the plates carry charges of equal magnitude and opposite directions.

A potential difference exists between the plates due to the charge.

Parallel Plate Capacitor

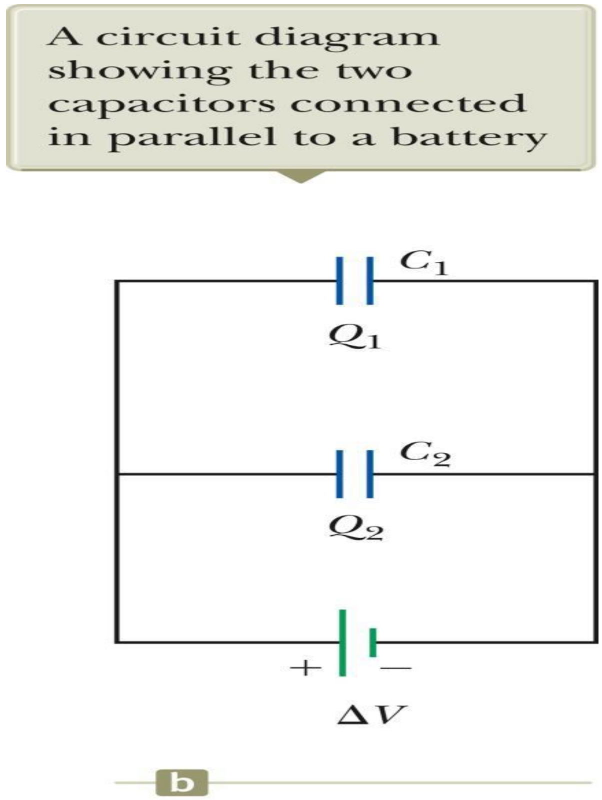
Each plate is connected to a terminal of the battery.

- The battery is a source of potential difference.

If the capacitor is initially uncharged, the battery establishes an electric field in the connecting wires.

The capacitors can be replaced with one capacitor with a capacitance of *equivalent capacitor* (C_{eq}.) .

- The C_{eq}. must have exactly the same external effect on the circuit as the original capacitors

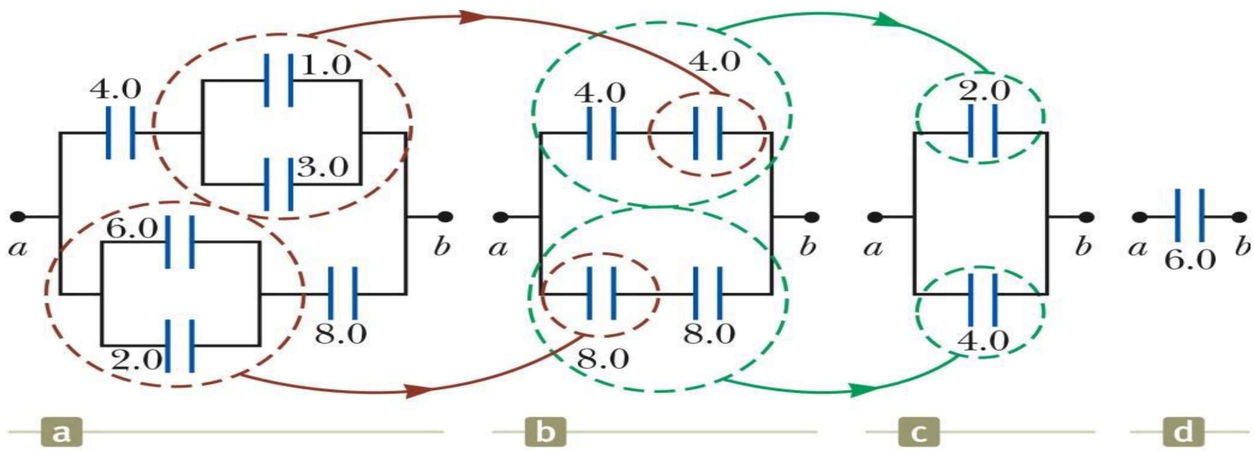


$C_{eq} = C_1 + C_2 + C_3 + \ldots$

The equivalent capacitance of a parallel combination of capacitors is greater than any of the individual capacitors.

Equivalent Capacitance, Example

The 1.0-mF and 3.0-mF capacitors are in parallel as are the 6.0-mF and 2.0-mF capacitors. These parallel combinations are in series with the capacitors next to them. The series combinations are in parallel and the final equivalent capacitance can be found.



Capacitance –Parallel Plates

The charge density on the plates is $\sigma = Q/A$.

 A is the area of each plate, the area of each plate is equal

 Q is the charge on each plate, equal with opposite signs

The electric field is uniform between the plates and zero elsewhere.

$$C = Q/V = Q/Ed = Q/\ Qd/\varepsilon_o\ A = \varepsilon_o\ A/d$$

$$C = \varepsilon_o\ A/d$$

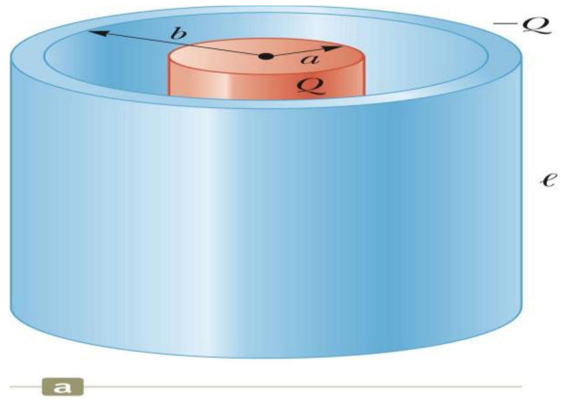
The capacitance is proportional to the area of its plates and inversely proportional to the distance between the plates

Capacitance of a Cylindrical Capacitor

$$V = -2k\ \lambda \ln(b/a)$$

Where $\lambda = Q/\ell$

The capacitance is C=Q/V= ℓ /2 k ln (b /a)



Capacitance of a Spherical Capacitor

The potential difference will be kQ(1/b-1/a)

The capacitance will be C=Q/V = ab/k(b-a)

Capacitors in Parallel

The capacitors can be replaced with one capacitor with a capacitance of *C*eq.

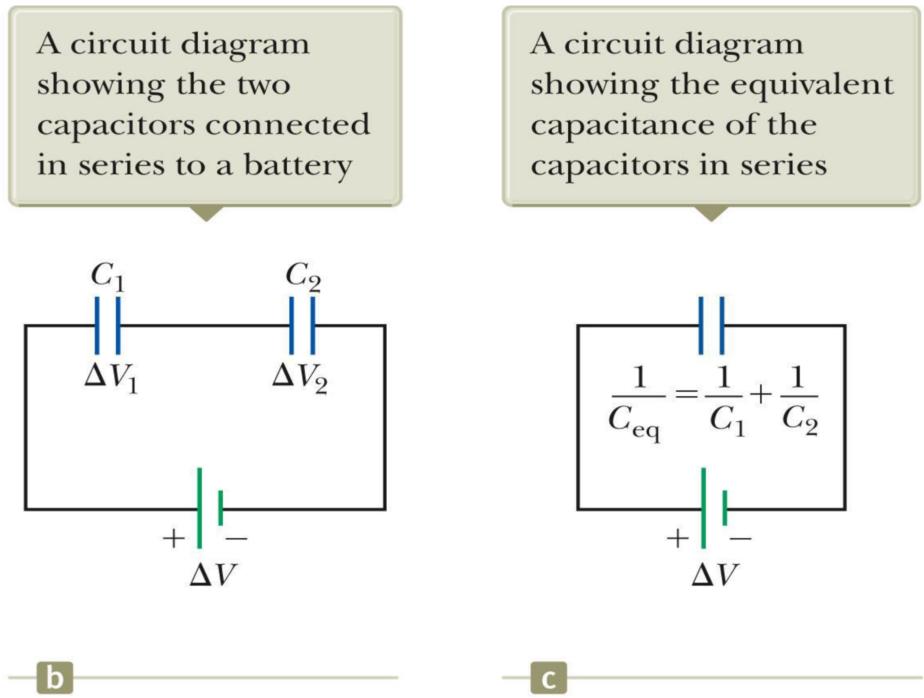
The *equivalent capacitor*must have exactly the same external effect on the circuit as the original capacitors.

Capacitors in Series

An equivalent capacitor can be found that performs the same function as the series combination.

The charges are all the same.

$$Q_1 = Q_2 = Q$$



Energy Stored in a Capacitor

Assume the capacitor is being charged, at some point, has a charge(q) on it.

The work needed to transfer a charge from one plate to the others

$$W=V\,dq = q/c\,dq$$

The total work required is $W = \int (q/C)\,dq = Q\,/2\,C$

The work done in charging the capacitor appears as electric potential energy

$$U=Q^2/2C = ½\,QV = 1/2CV^2$$

The energy stored increases as the charge increases and as the potential difference increases.

The energy can be considered to be stored in the electric field .

For a parallel-plate capacitor, the energy can be expressed in terms of the field as

$$U= ½\,(\varepsilon o A d)E^2.$$

It can also be expressed in terms of the energy density (energy per unit volume)

The energy density $(U/Ad) = \frac{1}{2} \varepsilon_o E^2$.

Capacitors with Dielectrics

A dielectric is a nonconducting material that, when placed between the plates of a capacitor, increases the capacitance. Dielectrics include rubber, glass, and waxed paper

With a dielectric, the capacitance becomes $C = \kappa C_o$.
κ is the dielectric constant of the material.

The capacitance increases by the factor κ when the dielectric completely fills the region between the plates.

If the capacitor remains connected to a battery, the voltage across the capacitor necessarily remains the same.
If the capacitor is disconnected from the battery, the capacitor is an isolated system and the charge remains the same.

For a parallel-plate capacitor,

$$C= \kappa (\varepsilon_o A) / d$$

d is limited by the electric discharge that could occur though the dielectric medium separating the plates.

In theory, *c*ould be made very small to create a very large capacitance.

In practice, there is a limit to *d*.

For a given *d*, the maximum voltage that can be applied to a capacitor without causing a discharge depends on the **dielectric strength** of the material.