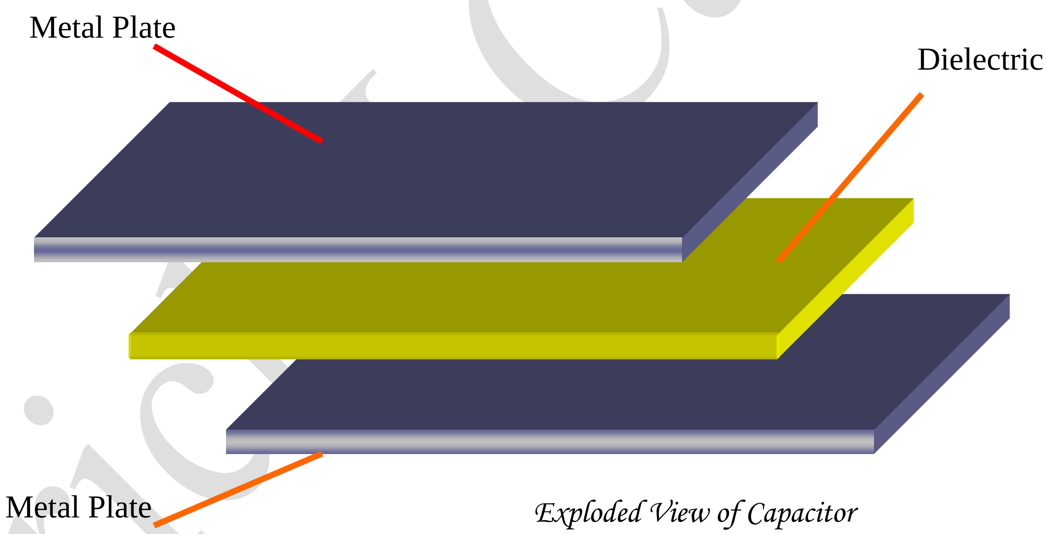
Capacitors

A capacitor is an electrical component that has the ability in storing charge.

Structurally a capacitor consists of two parallel metal plates, commonly made up of Aluminium with an insulator in between referred to as ***dielectric*****,** electrostatically separating or isolating the two plates from each other.
The dielectric may be air, paper, wax paper, perspex or any other material with high insulative properties.

Compact View of Capacitor



Exploded View of Capacitor

The Capacitance of a capacitor

Capacitance may be considered as the measurement of the extent to which a capacitor can store charge. It is its ability to store charge.

The capacitance is defined as the Charge on the plates of the capacitor per unit voltage across the plates of the capacitor.

$$C = \frac{Q}{V}$$

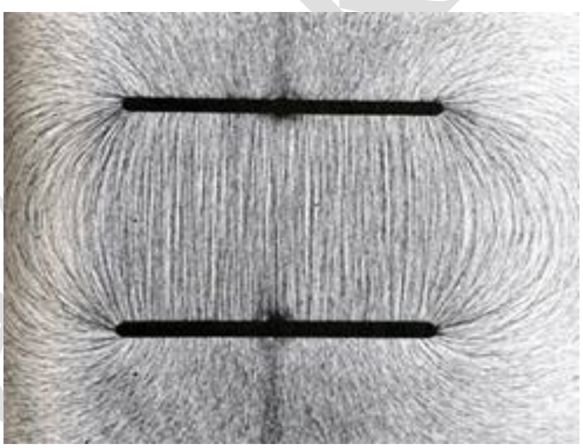
Units for Capacitance are faradays or farads in short symbol F.
Usually capacitance is denoted in terms of Microfaradays or Microfarads μF.
Incidentally 1 μF would be equivalent to $1X10^{-6}$ F in S.I. denomination or units.

Physical Factors that influence the capacitance of a capacitor

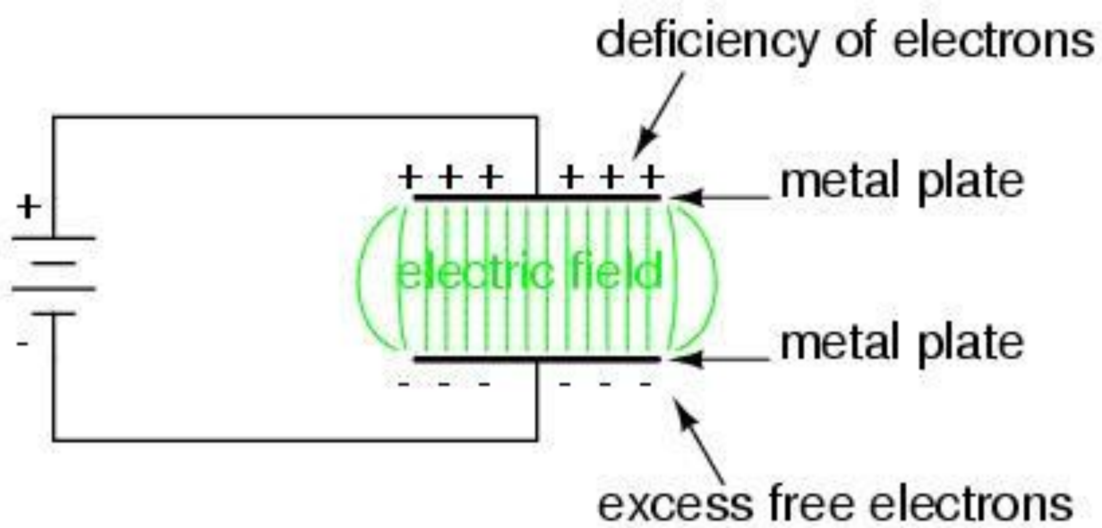
The capacitance of the capacitor depends upon three major physical characteristics that include:

a. The distance of plate
b. Area of overlap.
c. The permittivity of the dielectric

PS. It is important to note that everything about the structure of the capacitance is to maximize the electric field effect. The better the conservation of the electric field intensity between the plates is, the larger would be the concentration of charge per unit voltage on the plates of the capacitor.

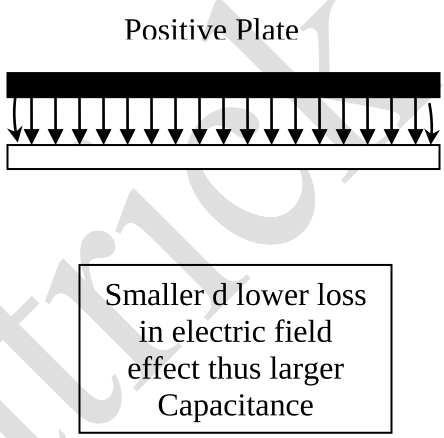


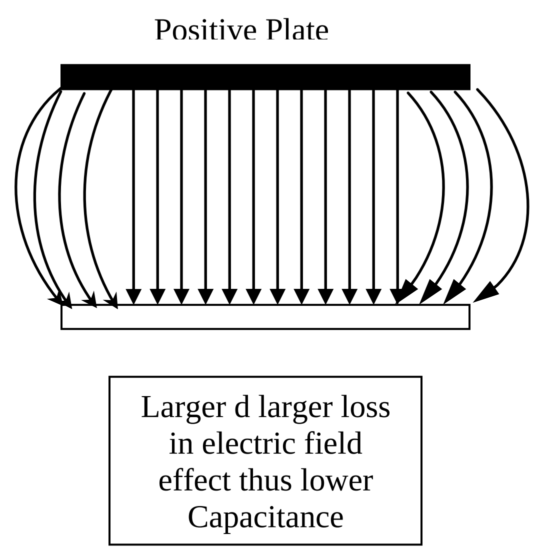
A photo deciphering the electric field intensity between two charged plates.



Distance of Plate separation‘d’.

The smaller the distance between the charged plates is, the lower would be loss of the electric field at the edges between the plates. In other words the more uniform the electric field would be in between the plates the more enhanced would be the effect of the charges on one plate to those of the other.





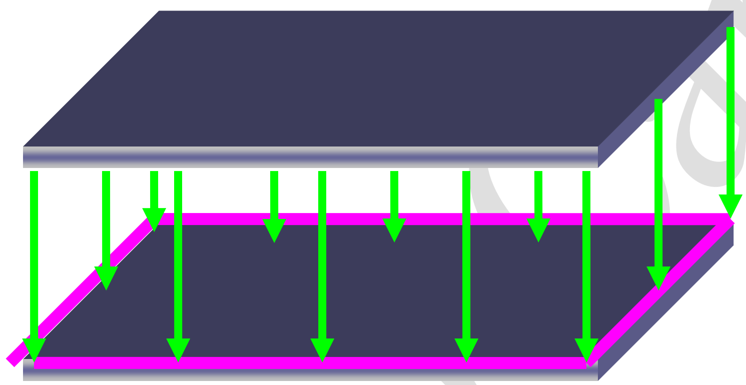
Thus: Capacitance is inversely proportional to distance of plate separation

$$C \ \alpha \ 1/d$$

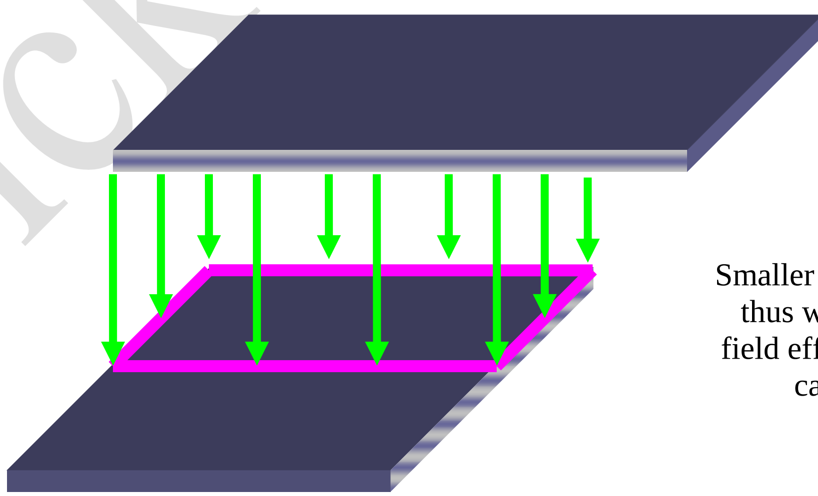
Capacitance and Area of Overlap between the plates

The larger the area of overlap between the plates the larger would be the electric field effect between the parallel plates of the capacitor. Therefore the larger would be the capacitance.

$$C \ \alpha \ A$$



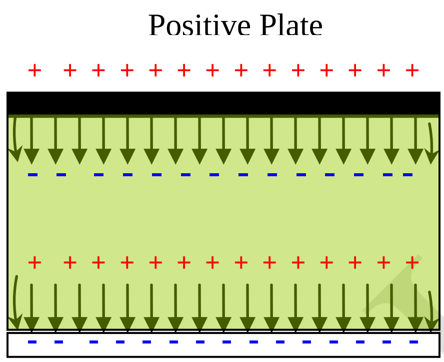
Large area of overlap, thus strong electric field effect and large capacitance



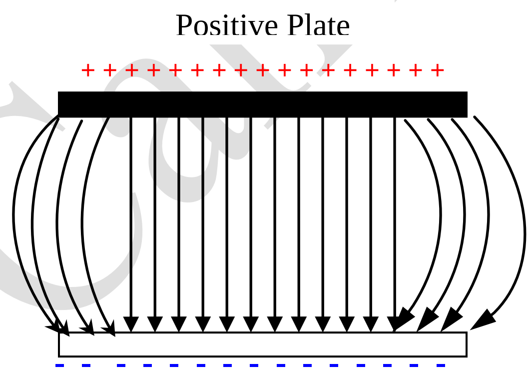
Smaller area of overlap, thus weaker electric field effect and smaller capacitance

The Permittivity of the dielectric

The dielectric and its nature play an important part in the capacitance of the capacitor. The dielectric is a material that even though it is insulative it tends to become highly ***polarized.*** Therefore even though it does not allow charge to jump from one plate to the other of the capacitor, it enhances the electric field effect. If in possession of a high ***permittivity* έ** and then it allows and enhances the transmission of the electric field from one plate to the other (high permittivity έ) but it does not allow the movement or migration of electrons from the negative plate to the positive plate where the electrons are in deficiency (low permeability μ).



Presence of dielectric reduces Electric field loss due to polarization therefore higher Capacitance



Absence of Dielectric causes electric field loss thus lower capacitance

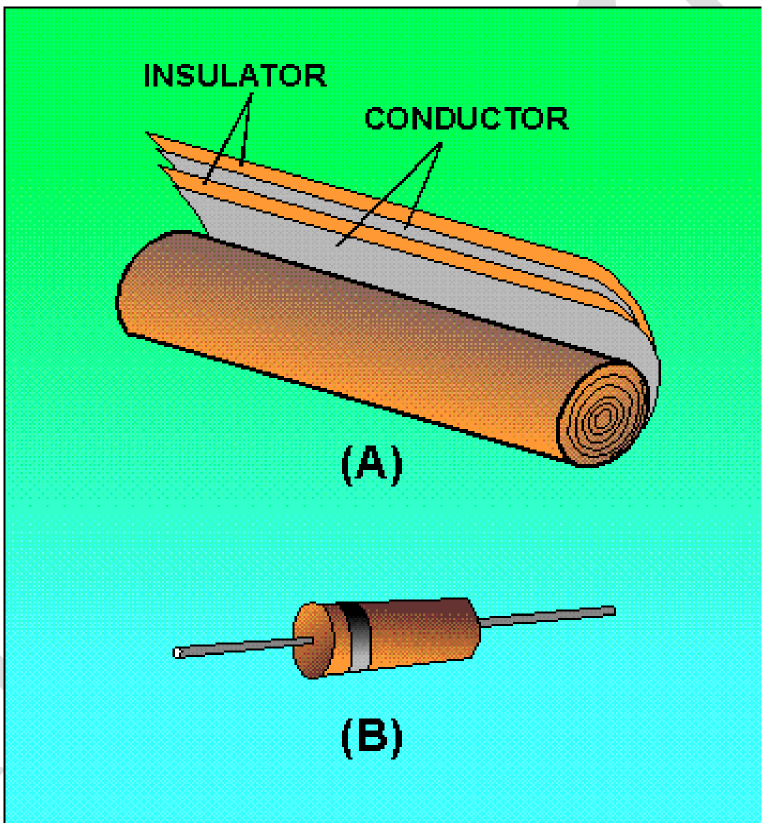
$$C \ \alpha \ \acute{\varepsilon}$$

Combining the three expressions together would provide the relationship:

$$C = \frac{\acute{\varepsilon} A}{d}$$

Therefore a good capacitor should be one that would have:

a. A small distance of plate separation.
b. A large area of overlap
c. A dielectric with a very good permittivity and a very low permeability.



Relative Permittivity $\acute{\varepsilon}_r$ and Relative Capacitance C_r.

The relative permittivity is the ratio of the permittivity of a dielectric to that of air. *(Incidentally unless otherwise stated the permittivity of air is taken to be equivalent to that of vacuum and is referred as the permittivity of free space ε_0)*
Thus

$$\text{Relative Permittivity of a material} = \frac{\text{Permittivity of named Material}}{\text{Permittivity of free space}}$$

$$\varepsilon_r = \frac{\varepsilon_{material}}{\varepsilon_0}$$

If the capacitance C of a capacitor $= \dfrac{\varepsilon A}{d}$

Then using a capacitor with air as a dielectric would give $C_0 = \dfrac{\varepsilon_0 A}{d}$ …….(i)

Where C_0 is the capacitance of a capacitor using air as a dielectric and ε_0 is the permittivity of free space

If the capacitor makes use of another dielectric for instance by replacing air with Perspex

then $C_P = \dfrac{\varepsilon_P A}{d}$ …….(ii)

Where C_P is the capacitance of a capacitor using air as a dielectric and ε_P is the permittivity of Perspex.
Dividing equation (ii) by equation (i): $C_R = \dfrac{C_P}{C_0} = \dfrac{\varepsilon_P A}{d} \Big/ \dfrac{\varepsilon_0 A}{d}$

Thus the relative capacitance $C_R = \dfrac{C_P}{C_0} = \dfrac{\varepsilon_P}{\varepsilon_0} = \varepsilon_R$

Types of Capacitors

Capacitors are used in electric circuits for various purposes. Different types of capacitors make use of different types of dielectrics. The choice of the dielectric usually depends on

the value of the capacitance and the stability required for the capacitor that is the way its capacitance will vary as it ages.
For every dielectric there is a specific potential gradient or a maximum potential above which the capacitance of the capacitor will break down. The breaking potential usually depends upon the permittivity and the thickness of the dielectric. Liquid and gaseous capacitors usually recover their original properties whenever the applied Pd is reduced below the breaking voltage, but this is not the case with many solid dielectrics.

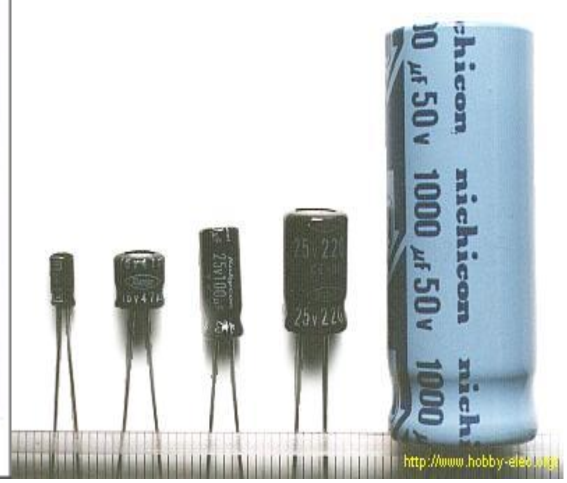
a. Paper, plastic, ceramic and mica capacitors

Uniform layers of waxed paper, plastics (like polystyrene), ceramics (like talc with barium titanate) and mica are all used for as dielectrics. Capacitance for these types of capacitors rarely exceeds a few microfarads and in the case of mica the upper limit is about 0.01μF.

b. Electrolytic Capacitors

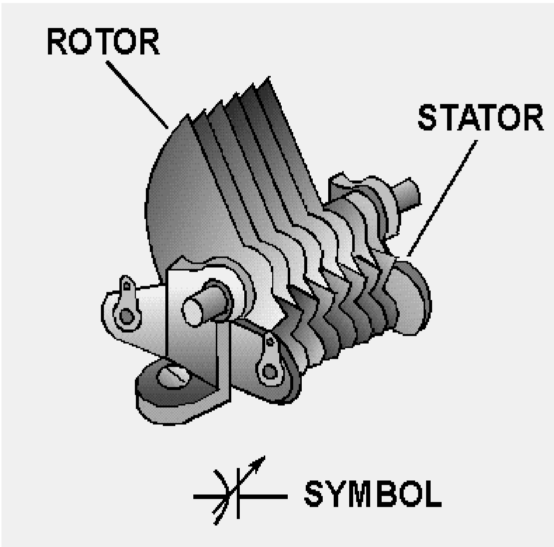
These have capacitances up to 10000 μF and are quiet compact because they employ very thin layers of dielectrics typically in the region of 10^{-3}mm and can withstand very high voltages without breaking down. The problem with electrolytic capacitors is that they have dedicated terminals and reversing the connections of an electrolytic capacitor would cause it breakdown beyond repair.
The film applied would usually involve a thin aluminium oxide film formed by passing a small current through a paper soaked with an aluminium borate solution separating two aluminium electrodes. The oxide forming on one of the electrodes would act as one of the plates of the capacitor.

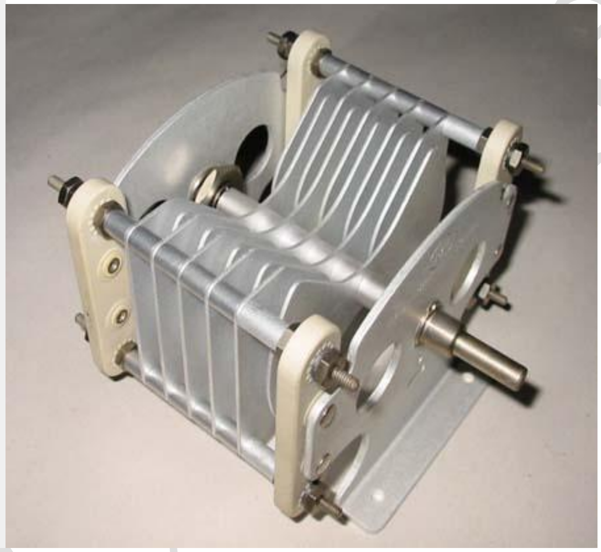

Element for Electrolytic Capacitors



c. Air Capacitors

Such capacitors find their use in radio tuning circuits. Air is used as the dielectric in variable capacitors. These consist of two sets of parallel a set of which is fixed while the other being able to be rotated on a spindle. Changing the area of overlap between the plates would vary the capacitance of the capacitor.

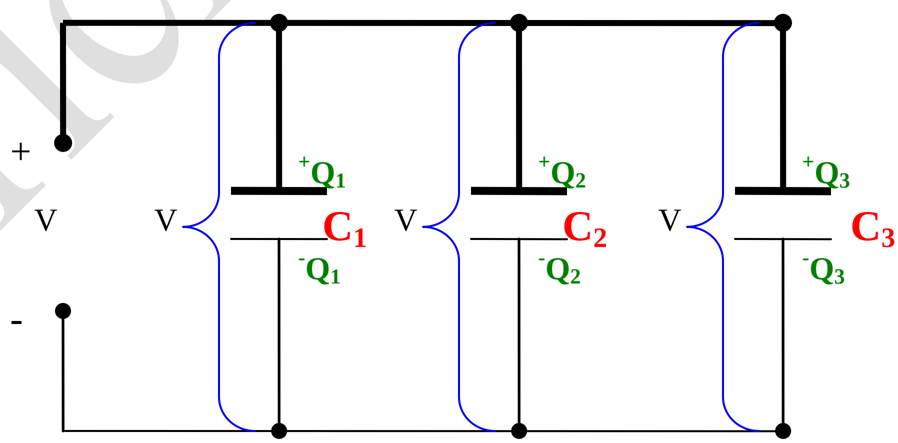




Capacitor Circuits or networks

a. Capacitors in parallel

Capacitors in parallel have common voltages across their plates but different charges that depend upon the capacitance of the capacitor.



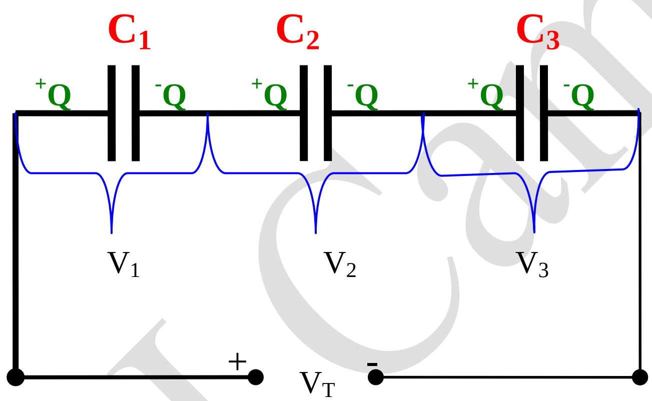
Thus: $Q_1 = C_1V$, $Q_2 = C_1V$, $Q_3 = C_3V$

If total charge $Q = Q_1 + Q_2 + Q_3$

Then $Q = V(C_1+C_2+C_3)$

b. Capacitors in series

Capacitors in series exhibit a common charge but have different voltages across them depending upon the capacitance of the capacitor.



If $V_T = V_1 + V_2 + V_3$

And $V = Q/C$

Then: $Q/C_T = Q/C_1 + Q/C_2 + Q/C_3$

Then Deleting Q would give:

$$1/C_T = 1/C_1 + 1/C_2 + 1/C_3$$

Energy stored in a capacitor:

A capacitor contains energy only if it contains charge. Once charging starts, electrons will accumulate on the plates of the capacitor. Thus the addition of further electrons would involve work to be done against the repulsive charge offered by negative charges already on the plates of the capacitor. Equally the removal of electrons from the plates of the capacitor would require that work is done against a force of attraction offered by the positive charges present on the plates of the capacitor the work which done is stored as electrical potential energy on the plates of the capacitor.

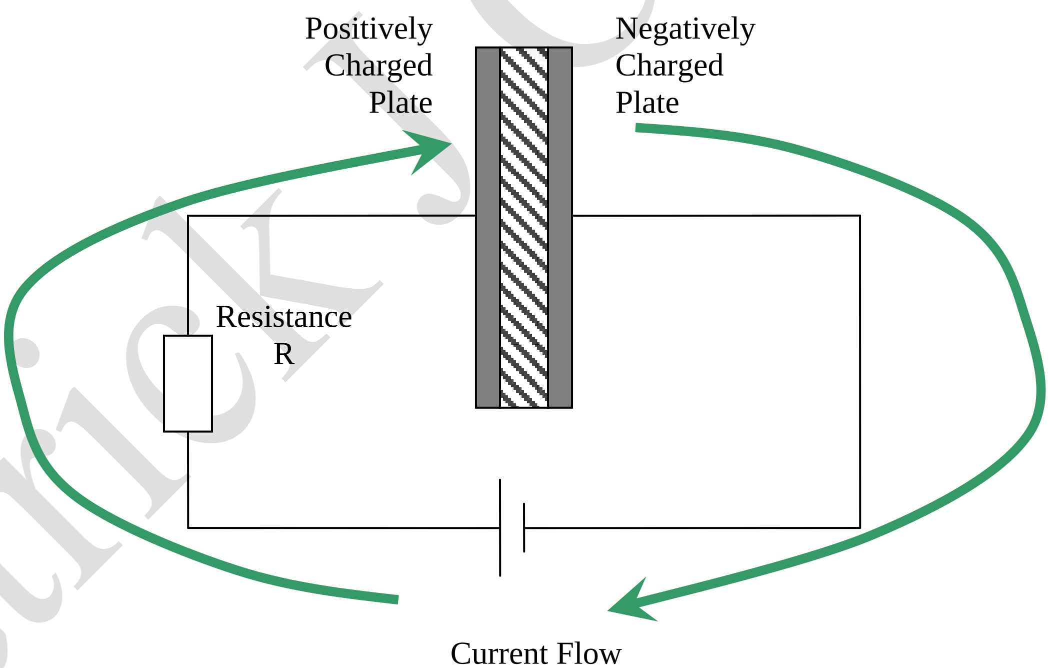
Let the energy stored on the plates of the capacitor = W Units Joules J
Let the capacitance of the capacitor = C Units farads F
Let the pd across the plates of the capacitor = V Units Volts V
Let the charge on the plates of the capacitor = Q Units Coulombs C

Thus Energy stored on the plates of the capacitor is :

$$W = Q^2/2C = \frac{1}{2}(CV^2) = \frac{1}{2}(QV)$$

Charging and discharging a capacitor

When the battery is connected to the capacitor there will be a momentary flow of current to the capacitor plates causing one plate to obtain a positive charge while the other will get a negative charge.



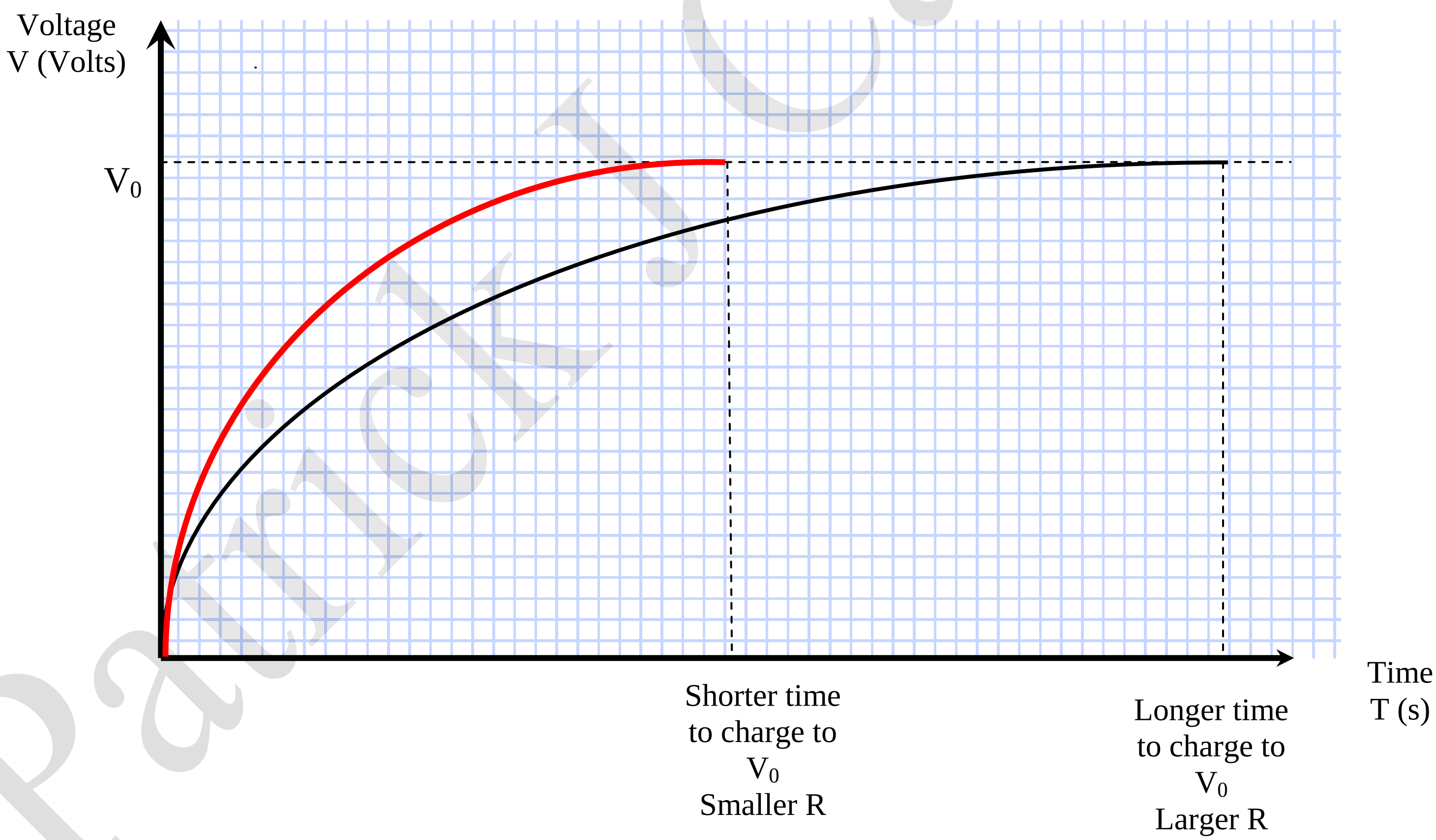
The Capacitor will stop charging when the p.d across its plates will become equal to that of the supply p.d. The time over which the capacitor would become fully charged is dependent upon various variables that include the capacitance of the capacitor and the resistance through which it is being charged.

Keeping the resistance R and the pd V constant, the larger the capacitance of the capacitor the larger would be the time that it would require to obtain the maximum pd across its plates.

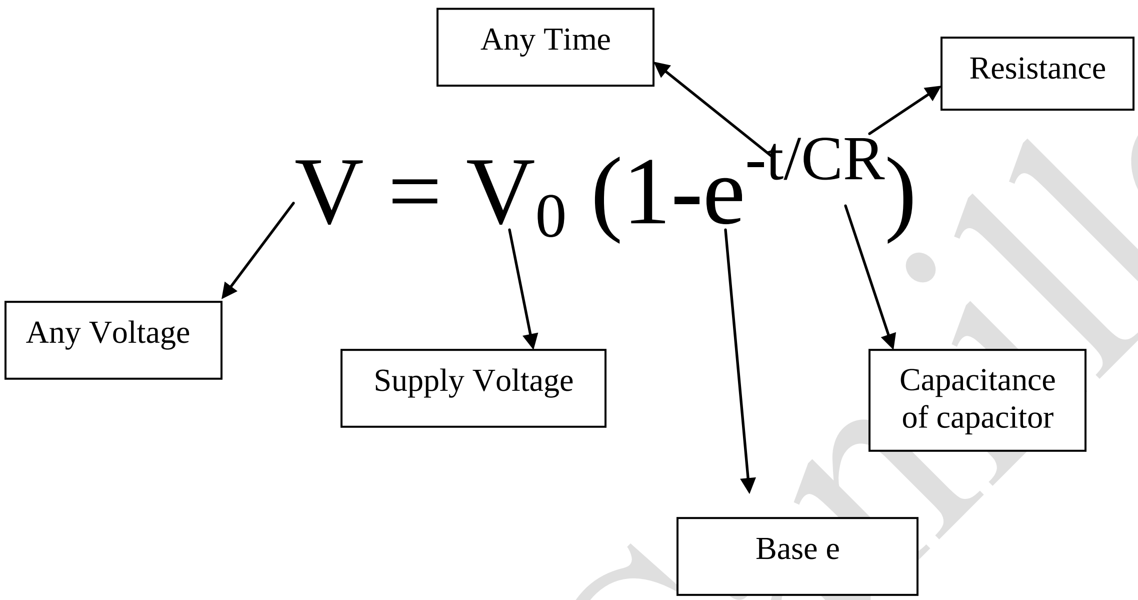
Keeping the pd V and the capacitance C across the plates constant the larger the resistance through which the capacitor charges is, the longer would be the time of charging.

The same would apply during discharging. A larger resistance through which the capacitor discharges or a large capacitance for the capacitor would imply that the capacitor would take a longer time to discharge.

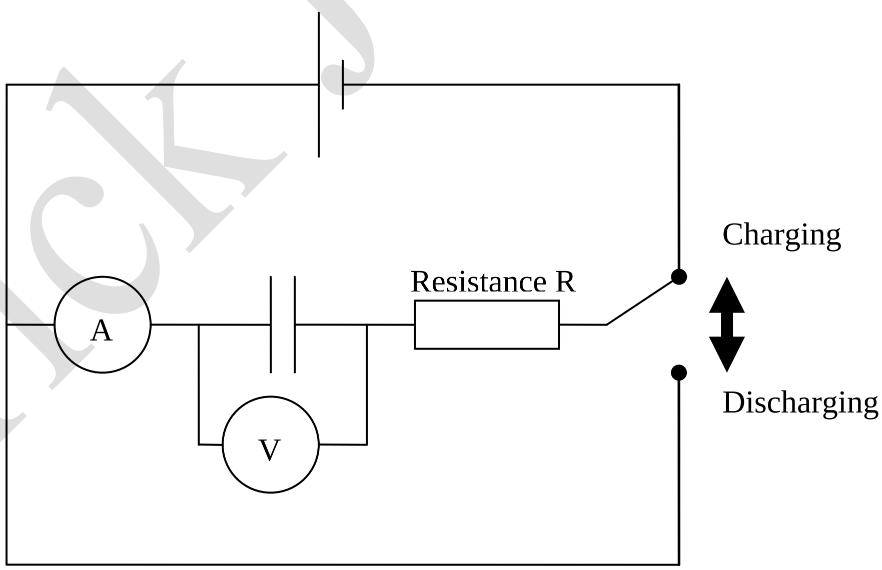
Graphical Representation of charging a capacitor by a pd V through a known resistance R



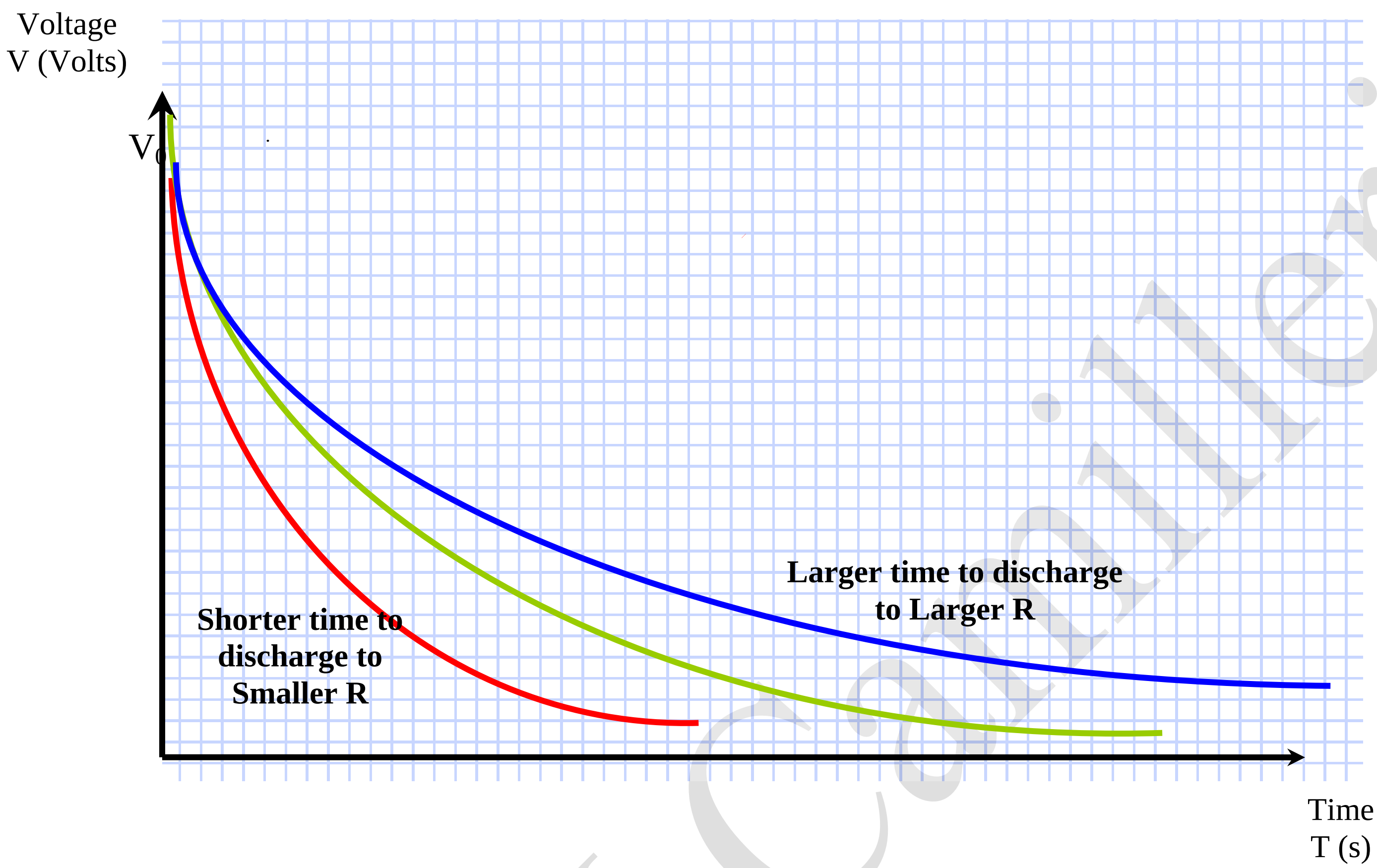
$$V = V_0 (1 - e^{-t/CR})$$

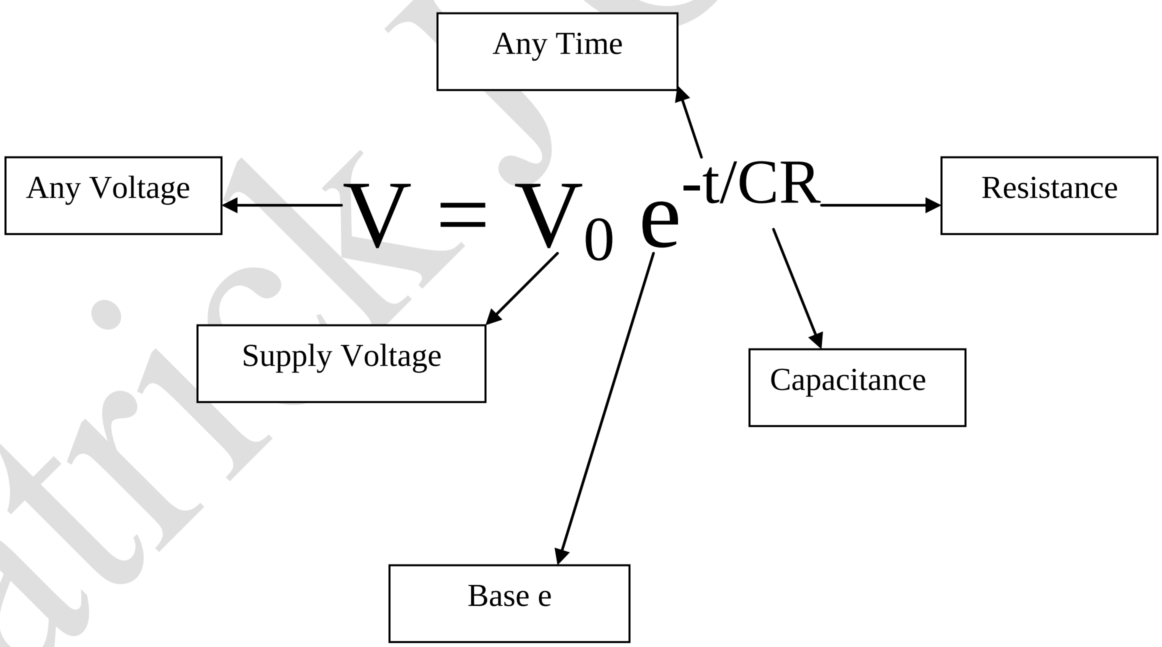


Discharging of a Capacitor through a known resistance R



When a capacitor is discharged through a known Resistance R and the pd across the resistance is gauged with time it is observed that it exponentially decreases with time and


Voltage
V (Volts)
V_0
Shorter time to discharge to Smaller R
Larger time to discharge to Larger R
Time
T (s)


Any Time
Any Voltage
$V = V_0\, e^{-t/CR}$
Resistance
Supply Voltage
Capacitance
Base e

Important times for charging and discharging include the half life $T_{1/2}$ and the time constant T.

The **Half Life time $T_{1/2}$** is the time required for the pd across or charge on the plates of the capacitor to:

1. Decrease by half during discharging.
2. Increase by half during charging.

Time constant T which is equal to CR is equivalent for the pd across the plates of the capacitor or the charge on the plates of the capacitor to:

1. Decrease to approximately 38% during discharging
2. Increase to approximately 63% during charging.

The Half Life Time and discharging:

During discharge the half life time $T_{1/2}$ would be equivalent for the pd V_0 to decrease to $V_0/2$.

Thus if for discharging $\mathbf{V = V_0 e^{-t/CR}}$

Then: $\mathbf{V_0/2 = V_0 e^{-T_{1/2}/CR}}$

Thus: $\mathbf{½ = e^{-T_{1/2}/CR}}$
$\mathbf{2 = e^{T_{1/2}/CR}}$ (Removal of negative sign will reduce ½ to 2)

$\mathbf{\ln 2 = T_{1/2}/CR}$

$\mathbf{0.6931 = T_{1/2}/CR}$
$\mathbf{0.6931CR = T_{1/2}}$

The Time Constant T and discharging:

When any time t is equal to the time constant T, then

If $V = V_0 e^{-t/CR}$ then $V = V_0 e^{-T/CR}$

Since T = CR then $V = V_0 e^{-CR/CR} = V = V_0 e^{-1}$

Or $V = V_0/e = 0.368V_0$

Thus when T= CR

$V = 0.368\ V_0$