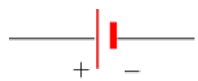
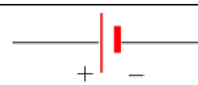
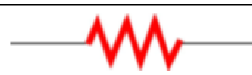
3.2 – Direct Current Circuit

There are two types of circuits – direct current (*dc*) and alternating current (*ac*) circuits.
DC circuits are the circuits where the voltage (current) is constant in time
AC circuits are circuits where the voltage (current) varies with time typically like a sine and cosine.

A ***source*** is a device that converts non-electrical energy to electrical energy are a battery which converts chemical energy to electrical energy and a generator which converts mechanical energy to electrical energy.

The circuit symbol for a *dc* source is



Voltage Source	
Resistor	
Switch	

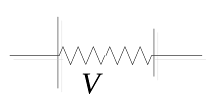
An ***electromotive force*** (***emf***) of a source is defined to be the amount of work done per a unit charge by the source in transferring a charge from one terminal to the other

$$\varepsilon = \frac{W_s}{q}$$

$E \rightarrow$ Electromotive force (εmf) of a source
$W_s \rightarrow$ Work done by the source in carrying a charge from one terminal to the other.

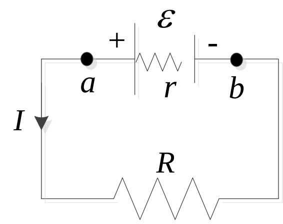
Unit of measurement of εmf is Joules/Coulomb which is the Volt (*V*).

Any source has an internal resistance is represented as



A Source Connected to a Source

Consider a source of *emf* ε and internal resistance r connected to an external resistance R as shown



Even though charge is carried by electrons, conventionally the direction of current is taken to be the direction of flow of positive charges.

The potential difference across the terminals of a source $\left(V_{ab}\right)$ is equal to the εmf of the source minus the potential drop across the internal resistance

$$\boxed{V_{ab} = \varepsilon - Ir}$$

I → Current

V_{ab} → Potential difference across the terminals of a source

Ir → Potential drop across the internal resistance of the source

The potential difference across the terminals of a source is equal to the potential drop across the external resistance.

$$V_{ab} = IR = V_R \quad \text{but } V_{ab} = \varepsilon - Ir$$

$$\varepsilon - Ir = IR \quad \Rightarrow \quad \varepsilon = IR + Ir$$

$$\boxed{I = \frac{\varepsilon}{R + r}}$$

Example

A battery of εmf 20 V and internal resistance 5 Ω is connected to an external resistance of 95 Ω.

a) Calculate the current in the circuit

b) Calculate the potential drop across the terminal of the battery

c) Calculate the potential drop across the external resistance

Solution

a) ***Given***: $\varepsilon = 20V, \quad r = 5\ \Omega, \quad R = 95\ \Omega$

$$I = \frac{\varepsilon}{R + r} = \frac{20}{95 + 5} = \frac{20}{100} \underline{= 0.2\ A|}$$

b) $V_{ab} = \varepsilon - Ir = 20 - 0.2(5) \underline{= 19\ V|}$

c) $V_R = IR = 0.2(95) \underline{= 19\ V|}$

Or $V_R = V_{ab} \underline{= 19\ V|}$

Power of a Source (P)

Power of a source is defined to be the rate of conversion of non electrical energy to electrical energy

$$\boxed{P_S = \frac{W_S}{\Delta t}}$$

$P_S \rightarrow$ Power of a source

$W_S \rightarrow$ Work done by a source in transporting charges from one to the other in a time Δt

But $\varepsilon = \frac{W_s}{q} \quad \Rightarrow \quad W_s = q\varepsilon$

$$P_S = \frac{W_S}{\Delta t} = \frac{q\varepsilon}{\Delta t} = \left(\frac{q}{\Delta t}\right)\varepsilon \qquad \text{but } I = \frac{q}{\Delta t}$$

$$\boxed{P_S = I\varepsilon}$$

$\rightarrow$ Power produced by a source equal to the product of the current and the *emf* of the source

Unit of power is *Joule/second* which is defined to be the watt (***W***).

The power delivered to the external resistance is equal to the power produced by the source minus the power dissipated in the internal resistance of the source.

$$\boxed{P_d = P_S - P_r}$$

$P_d \rightarrow$ Power delivered to the external resistance

$P_S \rightarrow$ Power produced by the source

$P_S \rightarrow$ Power dissipated in the internal resistance of the battery

But $P_S = \varepsilon I \quad \& \quad P_r = I^2 r$

$$\boxed{P_d = \varepsilon I - I^2 r}$$

The power dissipated in the external resistance by the source to the external resistance

$$\boxed{P_R = P_d}$$

$P_R \rightarrow$ Power dissipated in the external resistance

$$\boxed{P_R = \varepsilon I - I^2 r}$$

Also $\boxed{P_R = I^2 r}$

Example

A battery of *emf* 10 *V* and internal resistance 2 Ω is connected to an external resistance of 18 Ω.

a) Calculate the power produced by the source

b) Calculate the power delivered by the battery to the external resistance

c) Calculate the power dissipated in the external resistance

<u>Solution</u>

a) ***Given***: $\varepsilon = 10V, \quad r = 2\ \Omega, \quad R = 18\ \Omega$

$$I = \frac{\varepsilon}{R+r} = \frac{10}{2+18} = 0.5\ A$$

$$P_S = \varepsilon I = (10)(0.5) \ \underline{= 5\ W|}$$

b) $P_r = I^2 r = (0.5)^2 (2) = 0.5\ W$

$$P_d = P_S - P_r = 5 - 0.5 \ \underline{= 4.5\ W|}$$

c) $P_R = P_d \ \underline{= 4.5\ W|}$

Or $P_R = I^2 R = (0.5)^2 (18) \ \underline{= 4.5\ W|}$

Series Connection of resistors

Resistors are said to be connected in series if they are connected in a line as shown

Consider a series connection of resistors R_1, R_2, R_3, $\ldots$ connected to a potential difference ΔV.

The current through all the resistors will be the same because they are connected in a single line.

$$I = I_1 = I_2 = I_3 = \ldots$$

Where I is the total current.

The total potential difference is equal to the sum of the potential drops across the individual resistors

$$\Delta V = \Delta V_1 + \Delta V_2 + \Delta V_3 + \ldots$$

Equivalent Resistance

Equivalent Resistance of a combination of resistors is defined to be the ratio between the potential drop across the combination (ΔV) & the current across the combination.

$$\boxed{R_{eq} = \frac{\Delta V}{I}}$$

$R_{eq} \rightarrow$ Equivalent resistance

$\Delta V \rightarrow$ Total potential difference

$I \rightarrow$ Current

For series combination $\Delta V = \Delta V_1 + \Delta V_2 + \Delta V_3 + \ldots$

& $\quad \Delta V = IR_{eq};\ \Delta V_1 = IR_1;\ \Delta V_2 = IR_2;\ \ldots$

$$IR_{eq} = IR_1 + IR_2 + IR_3 + \ldots$$

$$\Rightarrow \quad \boxed{R_{eq} = R_1 + R_2 + R_3 + \ldots}$$

$R_{eq} \rightarrow$ Equivalent resistance of a series combination

Example

A 2Ω, a 4Ω, and a 6Ω resistors are connected in series and then connected to a potential of 24*V*

a) Calculate the current in the circuit

b) Calculate the potential difference across each resistor

Solution

a) ***Given***: $R_1 = 2\ \Omega, \quad R_2 = 4\ \Omega, \quad R_6 = 6\ \Omega, \quad \Delta V = 24V$

$$R_{eq} = R_1 + R_2 + R_3 = 2 + 4 + 6 = 12\Omega$$

$$I = \frac{\Delta V}{R_{eq}} = \frac{24}{12} \underline{= 2\ A|}$$

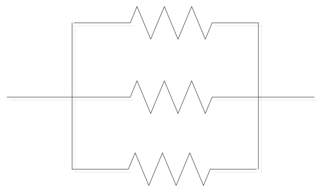
b) $\Delta V_1 = IR_1 = 2(2) \underline{= 4\ V|}$

$$\Delta V_2 = IR_2 = 2(4) \underline{= 8\ V|}$$

$$\Delta V_1 = IR_1 = 2(6) \underline{= 12\ V|}$$

Parallel Connection of Resistors

Resistors are said to be connected in parallel if they are connected in branches as shown



Resistors connected in parallel have the same potential difference across their terminals

$$\Delta V = \Delta V_1 = \Delta V_2 = \Delta V_3 = \cdots$$

Where ΔV is the total potential difference across the combination.

The total current across the combination is equal to the sum of the currents across the resistors

$$I = I_1 + I_2 + I_3 + \cdots$$

Where $I = \frac{\Delta V}{R_{eq}}$ is the total current across the combination.

Also $I_1 = \frac{\Delta V}{R_1};\ I_2 = \frac{\Delta V}{R_2};\ I_3 = \frac{\Delta V}{R_3};\ \cdots$

$$\frac{\Delta V}{R_{eq}} = \frac{\Delta V}{R_1} + \frac{\Delta V}{R_2} + \frac{\Delta V}{R_3} + \cdots$$

$$\Rightarrow \boxed{\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots}$$

Equivalent resistance of parallel combination

If there two resistors only, this expression can be simplified

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{R_2 + R_1}{R_1 R_2}$$

$$\boxed{R_{eq} = \frac{R_1 R_2}{R_2 + R_1}}$$

Example

A 2Ω, a 4Ω, and a 6Ω resistors are connected in parallel and then connected to a potential difference of 12V

a) Determine the potential difference across each resistor
b) Calculate the current across each resistor
c) Calculate the total current across the combination

Solution

a) Given: $R_1 = 2\ \Omega, \quad R_2 = 4\ \Omega, \quad R_6 = 6\ \Omega, \quad \Delta V = 12V$

$$\Delta V = \Delta V_1 = \Delta V_2 = \Delta V_3 \ \boxed{= 12\ V}$$

b)
$$I_1 = \frac{\Delta V_1}{R_1} = \frac{12}{2} \ \boxed{= 6\ A}$$

$$I_2 = \frac{\Delta V_2}{R_2} = \frac{12}{4} \ \boxed{= 3\ A}$$

$$I_3 = \frac{\Delta V_3}{R_3} = \frac{12}{6} \ \boxed{= 2\ A}$$

c)
$$I = I_1 + I_2 + I_3 = 6 + 3 + 2 \ \boxed{= 11\ A}$$

Or

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{2} + \frac{1}{4} + \frac{1}{6} = \frac{6+3+2}{12} = \frac{11}{12}$$

$$R_{eq} = \frac{12}{11}$$

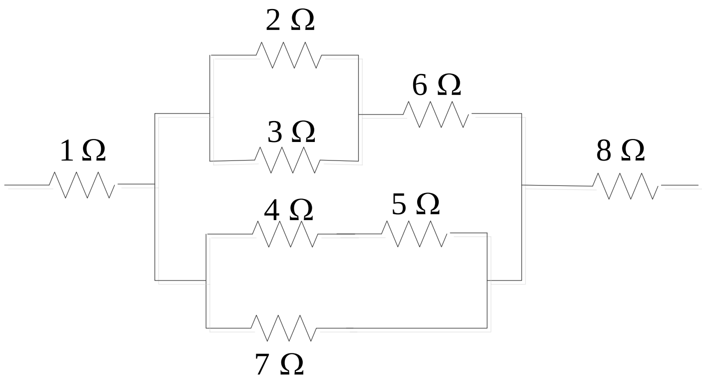
$$I = \frac{\Delta V}{R_{eq}} = \frac{12}{\frac{12}{11}} \ \boxed{= 11\ A}$$

Parallel Series Combinations

Parallel Series Combinations can be simplified by replacing each series or parallel combination by its equivalent resistance.

Example

Calculate the equivalent resistance of the following combination



Solution

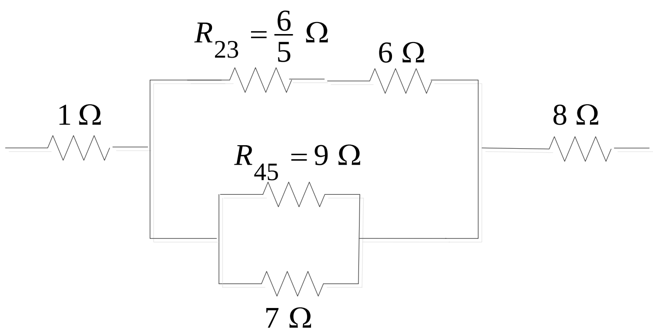
The 2Ω & 3Ω resistors are connected in parallel

$$R_{23} = \frac{R_2 R_3}{R_2 + R_3} = \frac{(2)(3)}{2+3} = \frac{6}{5}\Omega$$

The 4Ω & 5Ω resistors are connected in series

$$R_{45} = R_4 + R_5 = 4 + 5 = 9\Omega$$

And the circuit simplifies to



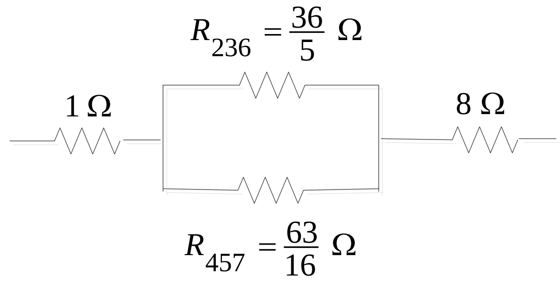
The R_{23} & 6Ω resistors are connected in series

$$\begin{aligned} R_{236} &= R_{23} + R_6 \\ &= \frac{6}{5} + 6 \\ &= \frac{36}{5}\ \Omega \end{aligned}$$

The R_{45} & 7Ω resistors are connected in parallel

$$R_{457} = \frac{R_{45}R_7}{R_{45}+R_7} = \frac{(9)(7)}{9+7} = \frac{63}{16}\ \Omega$$

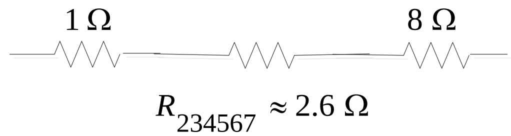
And the circuit simplifies to



The R_{236} & R_{457} resistors are connected in parallel

$$R_{234567} = \frac{R_{236}R_{457}}{R_{236}+R_{457}} = \frac{\left(\frac{36}{5}\right)\left(\frac{63}{16}\right)}{\frac{36}{5}+\frac{63}{16}} = \frac{(36)(63)}{(36\times 16)+(5\times 63)} \approx 2.6\ \Omega$$

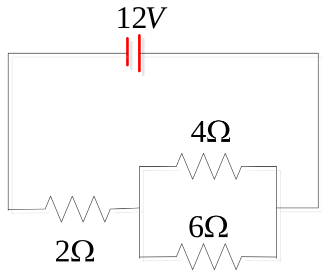
And the circuit simplifies to



$R_{eq} = 1 + 2.6 + 8 \underline{= 11.6\ \Omega}$

Example

A parallel combination of a 4Ω & 6Ω resistors are connected in series with a 2Ω resistor. Then the combination is connected to a 12V battery



a) Calculate the equivalent resistance of the combination

b) Calculate the current across each resistor

<u>Solution</u>

a) The 4Ω & 6Ω resistors are connected in parallel

$$R_{46} = \frac{R_4 R_6}{R_4 + R_6} = \frac{(4)(6)}{4+6} = 2.4\ \Omega$$

The R_{46} & 2Ω resistors are connected in series

$$R_{eq} = 2 + 2.4 = 4.4\ \Omega$$

b) R_{46} & R_2 are in series

$$I_{46} = I_2 = I = \frac{\Delta V}{R_{eq}} = \frac{12}{4.4} = 2.7\ A$$

R_4 & R_6 are in parallel

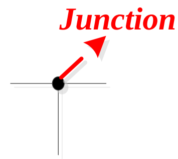
$$\Delta V_4 = \Delta V_6 = \Delta V_{46} = I_{46} R_{46} = (2.7)(2.4) \approx 6.5V$$

$$I_4 = \frac{\Delta V_4}{R_4} = \frac{6.5}{4} \approx 1.6\ A$$

$$I_6 = \frac{\Delta V_6}{R_6} = \frac{6.5}{6} \approx 1.1\ A$$

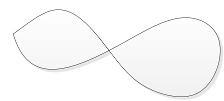
Kirchhoff's Rules

Kirchhoff's Rules are rules used to solve complex circuits.
A ***junction*** in a circuit is a point where two or more wires meet.



A ***simple loop*** is a non intersecting loop or a loop that is not divided into more than one loop

Simple loop



Not a simple loop

Kirchhoff's junction rules states that the sum of all the currents in a junction is zero

$$\sum_{junction} I = I_1 + I_2 + I_3 + \ \dots = 0$$

Sign Convention

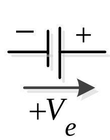
Currents directed towards the junction are taken to be positive while currents directed away from the junction are taken to be negative. It is easier to treat the variables as positive & represent a negative as the negative of the variable (***for example***, if a current I is negative it will be written as –*I*)

Kirchhoff's loop rules states that the sum of all the potential differences in a loop is zero

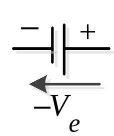
$$\sum_{loop} \Delta V = \Delta V_1 + \Delta V_2 + \Delta V_3 + \ \dots = 0$$

Sign Convention

The potential difference across a battery (source) is taken to be positive if transversed from its negative to its positive terminal & is taken to be negative if transversed from its positive terminal towards its negative terminal



Simple loop



Not a simple loop

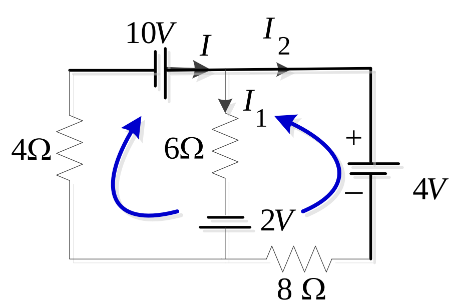
The potential difference across a resistor is taken to be negative if transversed in the direction of the current and positive if transversed opposite to the direction of the current

Applying Kirchhoff's loop

1. Assign variables & directions to the currents in all the wires of the circuit. Direction is assigned arbitrarily. If after solving the problem the current turns out to be positive, then the assigned direction is the correct direction. If the current turns out to be negative than the actual direction is opposite to the assigned direction.
2. Assign transverse directions (*i.e.*, clockwise or counterclockwise) to all of the simple loops of the circuit. Choice of a transverse direction is arbitrary. It is the direction in which Kirchhoff's loop rule is to be applied.
3. If there are *n* junctions, apply Kirchhoff's junction will not result in an independent equation.
4. Apply Kirchhoff's loop rule to all of the simple loops of the circuit.
5. Solve the resulting system of linear equations.

Example

Calculate the currents in the circuit shown below



Solution

There are two junctions, Kirchhoff's junction rule should be applied to one of them only

$I - I_1 - I_2 = 0 \quad \Rightarrow \quad I_2 = I - I_1$

I_2 has been eliminated sign and in the circuit. Hence for the $I - I_1$ will be used instead of I_2 .

Applying Kirchhoff's loop rule to the left simple loop (starting from the lower left corner)

$$-4I + 10 - 6I_1 + 2 = 0$$

$$4I + 6I_1 = 12$$

$$2I + 3I_1 = 6 \quad eq.(1)$$

Applying Kirchhoff's loop rule to the right simple loop (starting from the lower right corner)

$$4-6I_1+2+8\left(I-I_1\right)=0$$

$$6-6I_1+8I-8I_1=12$$

$$8I-14I_1=-6$$

$$4I-7I_1=-3 \quad eq.(2)$$

$$-2\begin{cases}2I+3I_1=6\\ 4I-7I_1=-3\end{cases} \rightarrow \begin{array}{r}-4I-6I_1=-12\\ 4I-7I_1=-3\\ \hline -13I_1=-15\end{array}$$

$$\boxed{I_1=\frac{15}{13}\,A}$$

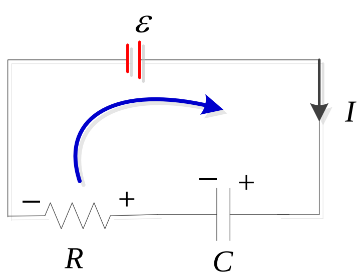
$$eq.(1)\rightarrow \quad 2I=6-\frac{45}{13}=\frac{33}{13} \quad \Rightarrow \boxed{I=\frac{33}{26}A}$$

$$I_2=I_1-I=\frac{33}{26}-\frac{15}{13}\boxed{=\frac{3}{26}\,A}$$

Since all the currents turned out to be positive, all the assigned directions of the currents were correct.

A battery connected to a series combination of a resistor and a capacitor

Consider a battery of emf and connected to a series combination of a resistor of resistance R and a capacitor of capacitance C.



Applying Kirchhoff's loop rule to this simple loop

$$\varepsilon-\frac{q}{C}-IR=0$$

Where q is the instantaneous charge of the capacitor but $I=\dfrac{dq}{dt}$

$$\varepsilon-\frac{q}{C}-\frac{dq}{dt}R=0$$

$$\frac{dq}{dt}R+\frac{q}{C}-\varepsilon=0$$

$$\frac{dq}{dt}+\frac{1}{RC}q-\frac{\varepsilon}{R}=0$$

$$\frac{dq}{dt}=\frac{\varepsilon}{R}-\frac{1}{RC}q$$

$$\frac{dq}{\frac{\varepsilon}{R}-\frac{1}{RC}q}=dt$$

$$\int\frac{dq}{\frac{\varepsilon}{R}-\frac{1}{RC}q}=\int dt \qquad \text{Let } u=\frac{\varepsilon}{R}-\frac{1}{RC}q \quad \Rightarrow \quad du=-\frac{1}{RC}dq$$

$$-RC\int\frac{du}{u}=\int dt$$

$$-RC\ln u=t+c_0$$

$$-RC\ln\left(\frac{\varepsilon}{R}-\frac{1}{RC}q\right)=t+c_0$$

$$\ln\left(\frac{\varepsilon}{R}-\frac{1}{RC}q\right)=-\frac{1}{RC}t+c_1$$

$$\frac{\varepsilon}{R}-\frac{1}{RC}q=e^{-\frac{1}{RC}t+c_1}$$

$$\frac{1}{RC}q=\frac{\varepsilon}{R}-e^{c_0}e^{-\frac{1}{RC}t}$$

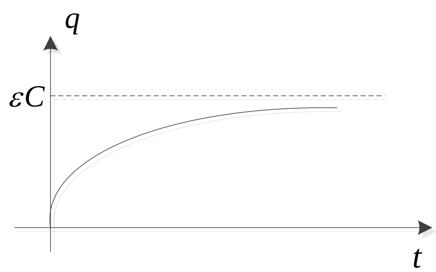
$$q=\varepsilon C-RCae^{-\frac{1}{RC}t}$$

If $q(0)=0$ (i.e. if initial charge of the capacitor is zero)

$$0=\varepsilon C-RCa$$

$$a=\frac{\varepsilon}{R}$$

$$q(t)=\varepsilon C-\varepsilon Ce^{-\frac{1}{RC}t}=\varepsilon C\left(1-e^{-\frac{1}{RC}t}\right)$$



The maximum charge (q_{max}) of the capacitor is equal to εC: $q_{max}=\varepsilon C$

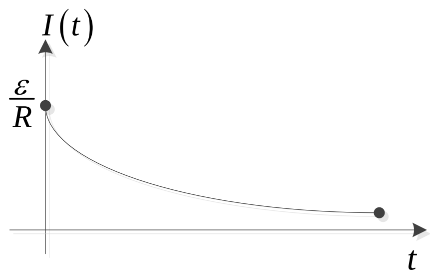
$$\boxed{q=q_{max}\left(1-e^{-\frac{1}{RC}t}\right)}$$

Instantaneous current:

$$I = \frac{dq}{dt} = \frac{d}{dt}\left[\varepsilon C\left(1 - e^{-\frac{1}{RC}t}\right)\right]$$

$$= \varepsilon C\left(\frac{1}{RC}e^{-\frac{1}{RC}t}\right)$$

$$= \frac{\varepsilon}{R}e^{-\frac{1}{RC}t}$$

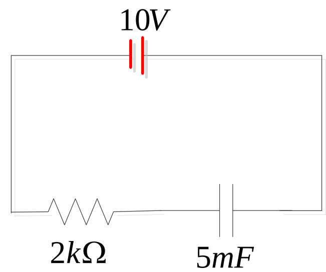


The maximum current $\left(I_{max}\right)$ occurs at $t = 0$ & is equal to $\frac{\varepsilon}{R}$

$$\boxed{I(t) = I_{\max} e^{-\frac{1}{RC}t}}$$

Example

A $2k\Omega$ resistor and a $5\ mF$ capacitor are connected in series and then connected to a $10V$ battery as shown



a) Calculate the charge in the capacitor at $t=0$, $t=10s$ & $t=\infty$

b) Calculate the current in the circuit at $t=0$, $t=10s$ & $t=\infty$

<u>Solution</u>

a) ***Given***: $\varepsilon = 10V$, $R = 2\times 10^3\Omega$, $C = 5\times 10^{-3}F$

$$q(t) = \varepsilon C\left(1 - e^{-\frac{1}{RC}t}\right)$$

At $t=0$ $\qquad q(0) = \varepsilon C\left(1 - e^{-\frac{1}{RC}0}\right) \underline{= 0|}$

At $t = 10s$

$$q(10) = (10)\left(5\times 10^{-3}\right)\left(1 - e^{-\frac{1}{\left(2\times 10^3\right)\left(5\times 10^{-3}\right)}10}\right)$$

$$= \left(5\times 10^{-2}\right)\left(1 - e^{-1}\right)$$

$$\underline{\approx 3.16\times 10^{-2}C|}$$

At $t=\infty$

$$q(0) = (10)\left(5\times 10^{-3}\right)\left(1 - e^{-\frac{1}{RC}\infty}\right)$$

$$= \left(5\times 10^{-2}\right)(1-0)$$

$$\underline{\approx 5\times 10^{-2}C|}$$

b) $I(t) = \frac{\varepsilon}{R}e^{-\frac{1}{RC}t}$

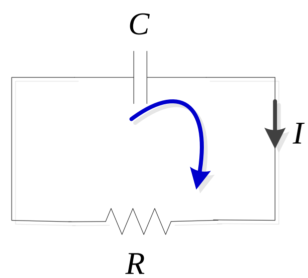
At $t=0$ $\qquad I(0) = \frac{10}{2\times 10^3}e^{-\frac{1}{RC}0} \underline{= 5\times 10^{-3}A|}$

At $t = 10s$ $\quad I(10) = \frac{10}{2\times10^3} e^{-\frac{1}{(2\times10^3)(5\times10^{-3})}10} \approx 1.8\times10^{-3} A$

At $t = \infty$ $\quad I(t) = \frac{10}{2\times10^3} e^{-\infty} \approx 0 A$

A Charged Capacitor connected to a Resistor

Using Kirchhoff's rules and transversing in the direction of the current as shown



$$-\frac{q}{C} - IR = 0$$ (same sign convention as resistor applies to the capacitor because it is not a source)

$$\Rightarrow IR = -\frac{q}{C}$$

but $I = \frac{dq}{dt}$

$$R\frac{dq}{dt} = -\frac{q}{C}$$

$$\frac{dq}{q} = -\frac{1}{RC}dt$$

$$\int \frac{dq}{q} = -\frac{1}{RC}\int dt$$

$$\ln q = -\frac{1}{RC}t + c_0$$

$$q = e^{-\frac{1}{RC}t + c_0}$$

$$q(t) = e^{c_0} e^{-\frac{1}{RC}t}$$

If $q(0) = Q_0$ (i.e. if initial charge of the capacitor is zero)

$$Q_0 = e^{c_0} e^0 = e^{c_0}$$

$$\boxed{q(t) = Q_0 e^{-\frac{1}{RC}t}}$$

And $I(t) = \frac{dq}{dt} = -\frac{Q_0}{RC} e^{-\frac{1}{RC}t}$ $\quad$ but $\frac{Q_0}{C} = \Delta V_0 \rightarrow$ Initial potential difference across the capacitor

$$I(t) = \frac{\Delta V_0}{R} e^{-\frac{1}{RC}t}$$

If the initial current is I_0 ; i.e. $I(t=0) = I_0$

$$I(0) = \frac{\Delta V_0}{R} e^{-\frac{1}{RC}0} \quad \Rightarrow \quad I_0 = \frac{\Delta V_0}{R}$$

$$\boxed{I(t) = I_0 e^{-\frac{1}{RC}t}}$$

Example

A $5mF$ capacitor is connected to a $10V$ battery. Then it is disconnected from the battery and then connect to a $2k\Omega$ resistor

a) Calculate the initial charge of the capacitor (just before it is connected to the resistor)

b) Find an expression for the charge in the capacitor as a function of time

c) Calculate the charge in the capacitor after 20s.

d) Find an expression for the instantaneous current as a function of time.

e) Calculate the current after half an hour (t = 30s)

Solution

a) Given: $\Delta V_0 = 10V, \quad R = 2\times 10^3 \Omega, \quad C = 5\times 10^{-3} F$

$$Q_0 = \Delta V_0 \cdot C = 10\left(5\times 10^{-3}\right) \underline{= 5\times 10^{-2}\ C}$$

b) $q(t) = Q_0 e^{-\frac{1}{RC}t}$

$$= 5\times 10^{-2} e^{-\frac{1}{\left(2\times 10^3\right)\left(5\times 10^{-3}\right)}t}$$

$$\underline{= 0.05 e^{-\frac{t}{10}}\ C}$$

c) $q(t) = 0.005 e^{-\frac{20}{10}} \underline{= 0.0068\ C}$

d) $I(t) = \frac{\Delta V_0}{R} e^{-\frac{1}{RC}t}$

$$= \frac{10}{2\times 10^3} e^{-\frac{1}{\left(2\times 10^3\right)\left(5\times 10^{-3}\right)}t}$$

$$\underline{= 0.005 e^{-\frac{t}{10}}\ A}$$

e) $I(30) = 0.005 e^{-\frac{30}{10}} \underline{= 2.4\times 10^{-4}\ A}$