Lecture-02: Basic Circuit Elements

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Concepts of Electrical Circuit

Some Terminology Related to a Circuit:

When analyzing either DC or AC circuits using Kirchoffs Circuit Laws, a number of definitions and terminologies are used to describe the parts of the circuit being analyzed such as: node, paths, branches, loops and meshes. These terms are used frequently in circuit analysis so it is important to understand them.

Circuit:

- Circuit is a path of conductors which, when complete, allows an electric current to flow. It is a loop that has a start point- a route- an end point.
- A circuit is necessary for current to flow. A circuit must close to be complete to flow current through it.
- These circuits are either in series or parallel:

Series circuit:

- Has a single loop for electrons to travel round.
- Components are connected one after another
- Current has to travel through all components
- Current is the same at all points
- Voltage is shared between components

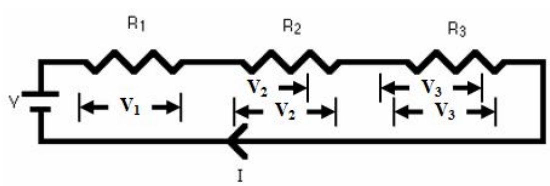

Figure: A series circuit

Parallel circuit:

- Has two or more paths for electrons to flow down
- Current is shared between the branches
- Sum of the current in each branch = total current
- Voltage loss is the same across all components

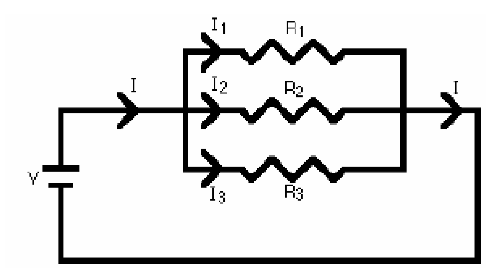

Figure: A parallel circuit

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Circuit Parameters:

- Various elements of an electric circuit are called its parameters like resistor, inductor, capacitor, voltage source, current source etc.

Active Elements of a Circuit:

- Those elements of a circuit which are able to supply energy to the network are called active elements of the circuit.
- Voltage source and current source are two active elements of a circuit.
- Current and voltage sources are of two types: independent source and dependent source.
    - A source that is not affected by changes in the connected circuit variables is an independent source.
    - A dependent source is affected by changes in some described manner with the conditions on the connected circuit. That is, the source quantity is controlled by another voltage or current.

Passive Elements of a Circuit:

- Passive elements do not supply energy to the network; instead they take energy from the sources and either convert it to another form or store it in an electric or magnetic field.
- Resistors, inductors and capacitors are passive circuit elements.

Linear Circuit:

- A linear circuit is one whose parameters (such as resistance, inductance, capacitance, waveform, frequency etc) are constant i.e. they do not change with voltage or current.
- In a linear circuit, voltage to current characterstics of the circuit are linear. That is current flowing through a circuit is directly proportional to the applied voltage. If we increase the applied voltage, then the current flowing through the circuit will also increase, and vice versa.
- In order for a circuit to be considered as linear, it must not contain any form of nonlinear component like diode, transistor, transformer etc.

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- A linear circuit must possess a superposition or thevenin's property.
- Examples of liner circuits and linear elements are resistor and resistive circuit, inductor and inductive circuits, capacitor and capacitive circuits.
- Figure below shows a linear circuit.

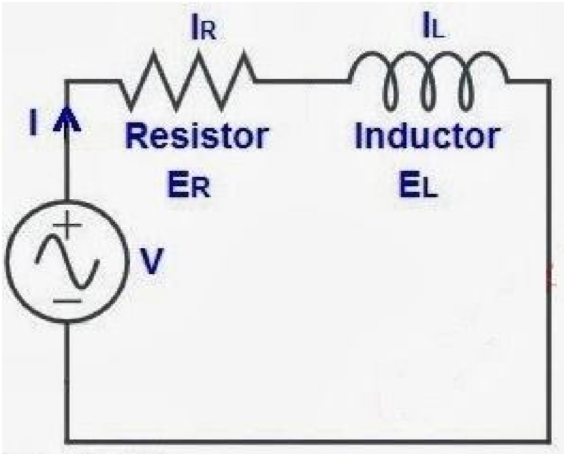

Figure: Linear circuit

- In a linear circuit, if we draw the output characteristic in between current and voltage, it will look like a straight line as shown in figure below.

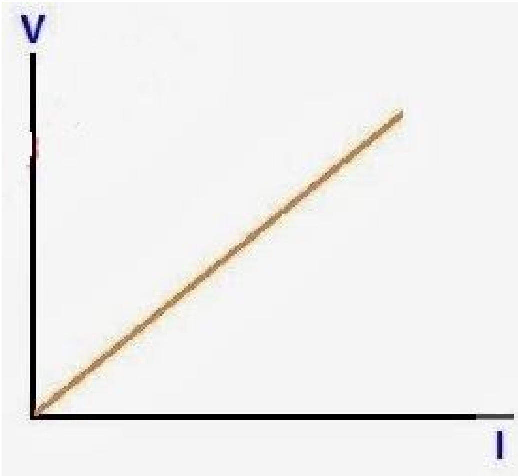

Figure: Linear characteristics curve

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Non-linear Circuit:

- A non-linear circuit is one whose parameters change with voltage or current. In other words, an electric circuit in which circuit parameters (like resistance, inductance, capacitance, waveform, frequency etc) is not constant, is called non-linear circuit.
- A nonlinear circuit contains nonlinear components like diode, transistor, transformer etc, which fall subject to shorting or failure that can result in the malfunction of the circuit-protecting device.
- Superposition or Thevenin's theorem can not be used for a non-linear circuit.
- Figure below shows a non-linear circuit.

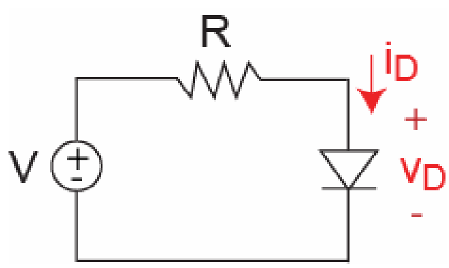

Figure: Non-linear circuit

- In a non-linear circuit, if we draw the output characteristic curve in between current and voltage, it will look like a curved or bending line as shown in figure below.

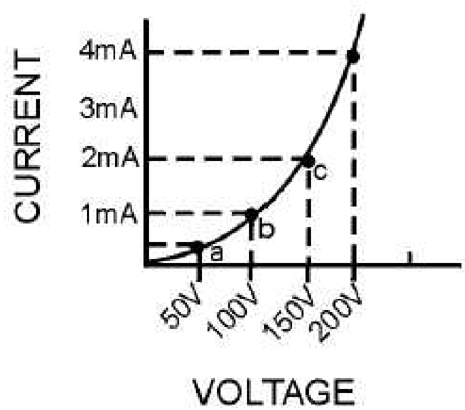

Figure: Non-linear characteristics curve

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Bilateral Circuit:

- A bilateral circuit is one whose properties are the same in either direction.
- The term is typically used for components in electrical circuits. For example, a resistor behaves the same way no matter if it is connected left-to-right or right-to-left.
- Bilateral circuit elements are resistor, capacitor and inductor.

Unilateral Circuit:

- A unilateral circuit is one whose properties change with the direction of its operation.
- A circuit containing a diode is a unilateral circuit, because it conducts current in one direction (forward bias mode), and does not conduct in the other direction (reverse bias mode).
- Unilateral circuit elements are diode, transistor, etc.

Electric Network:

- A combination of various electric elements, connected in any manner whatsoever, is called an electric network.

Passive Network:

- It is a kind of electric network which contains no source of e.m.f. in it.

Active Network:

- It is a kind of electric network which contains one or more than one source of e.m.f. in it.

Path:

- A line of connecting elements or sources with no elements or sources included more than once.

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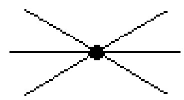
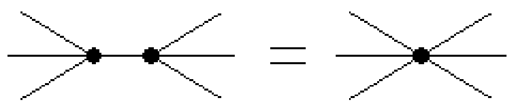
Node:

- It is a junction, connection or terminal in a circuit where two or more circuit elements are connected together.
- A node is indicated by a dot.
- Nodes have no electrical properties of their own and are only a mean to connect circuit parts together.
- Figure below shows an example of a simple node.
- A node acts like an intersection of flowing currents.

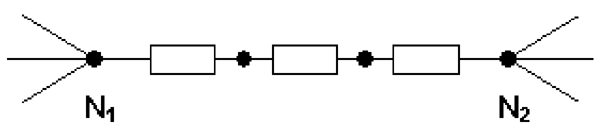


- Note that, two nodes connected together with a short are one. Because the length of a short doesn't matter and you can put these two nodes it the same spot, making just one node, as shown below:



Branch:

- It is a part of a network which lies between any two nodes, consisting of one or more components connected in series.
- There would be no other branches connected in-between the two nodes of one branch.
- Figure below shows an example of a branches between nodes N_1 and N_2.



Loop:

- It is a close path in a circuit in which no elements or node is encountered more than once.

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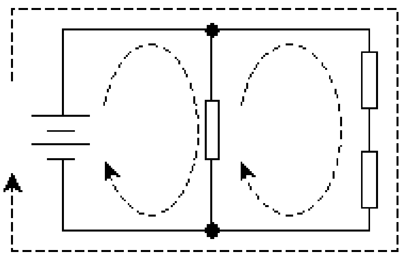
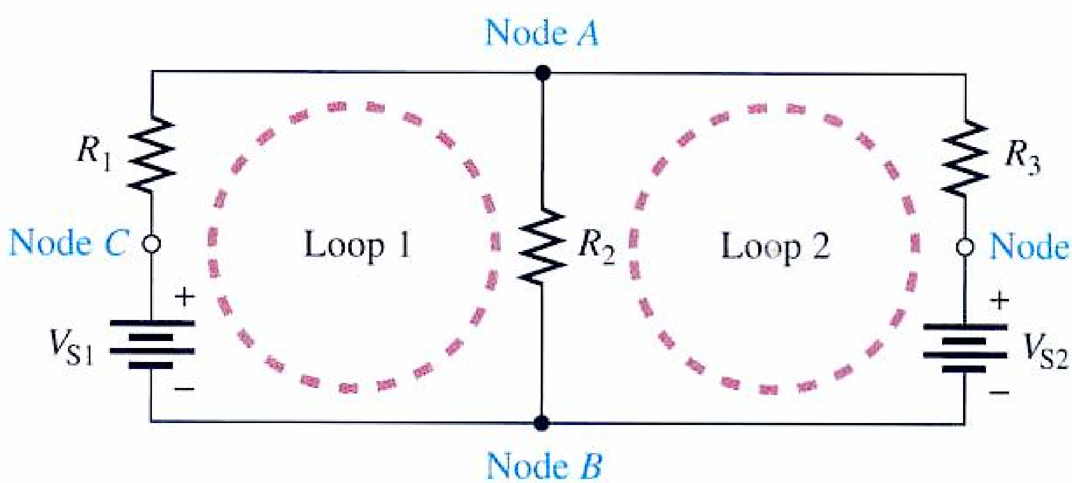
Mesh:

- A mesh in a circuit is any close loop starting and ending with the same node, not passing any node or branch twice.
- A mesh contains no other loop within it.
- Figure below shows three different meshes for a circuit.





The Open Circuit

- The open circuit is a very basic circuit that we should all be very familiar with.
- It is the circuit in which no current flows because there is an open in the circuit that does not allow current to flow.
- Two points are said to be open-circuited when there is no direct connection between them.
- Since an 'open' represents a break in the continuity of the circuit, it gives rise to two important factors:

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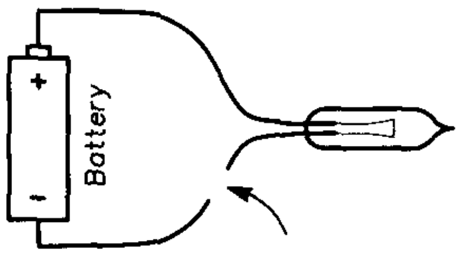
- Resistance between the two points is infinite.
- There is no flow of current between the two points.

- A good example is a light switch. When the light is turned off, the switch creates an opening in the circuit, and current can no longer flow.
- A fuse is a device that is used to create an open circuit when too much current is flowing.



Example: Open in a Series Circuit (1.22 Page-30)

The Short Circuit

- A short circuit is an accidental path of low resistance which passes an abnormally high amount of current.
- When two points of circuit are connected together by a thick metallic wire, they are said to be short-circuited.
- A short often occurs as a result of improper wiring or broken insulation.
- Since 'short' has practically zero resistance, it gives rise to two important factors:
  - No voltage can exist across it, because $V=IR=I\times0=0$.
  - Current through it (called short-circuit current) is very large (theoretically, infinity), because $I=V/R=V/0=\infty$.
- Therefore a short circuit will have too much current flowing through it and may even cause the power source to be destroyed.
- Short circuits can produce very high temperatures due to the high power dissipation in the circuit.

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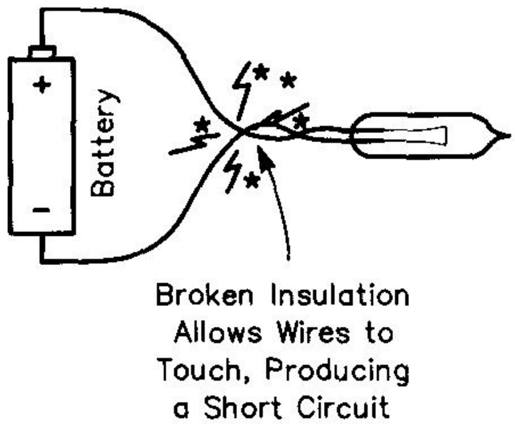
- What's the best way to stop a short circuit from doing damage (because it is drawing too much power from the source)?—By using a fuse. Fuses are designed to work up to a certain amount of current (e.g. 1 amp, 15 amps, etc). When that maximum current is exceeded, then the wire within the fuse burns up from the heat of the current flow. With the fuse burnt up, there is now an "open circuit" and no more current flows.
- A short circuit may be in a direct- or alternating-current (DC or AC) circuit. If it is a battery that is shorted, the battery will be discharged very quickly and will heat up due to the high current flow.



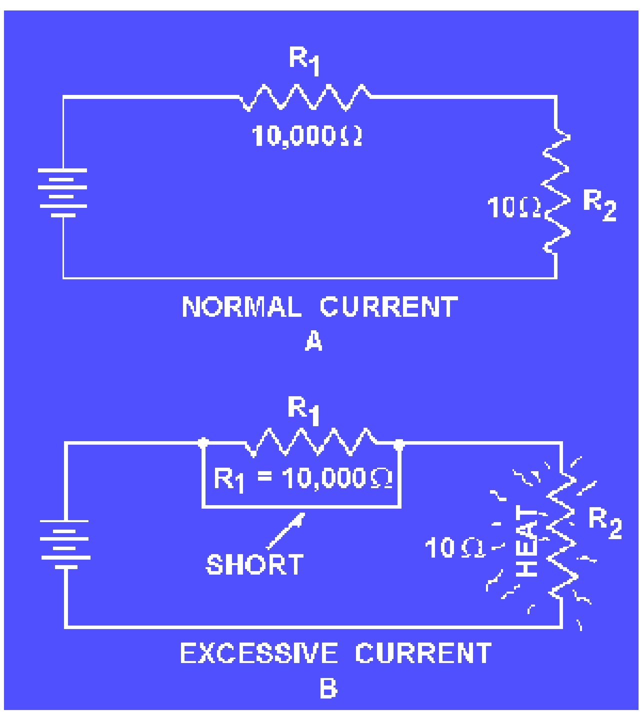


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Figure: Normal and short circuit conditions.

Since the resistor has in effect been replaced with a piece of wire, practically all the current flows through the short and very little current flows through the resistor. Due to the excessive current flow, the 10-ohm resistor becomes heated. As it attempts to dissipate this heat, the resistor will probably be destroyed.

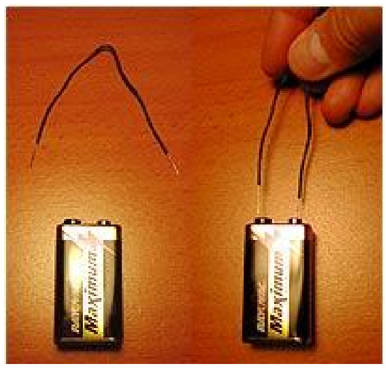

Figure: The simplest example of a 'short circuit'.

All you need is a battery and a piece of wire. If you do this in dark, you may notice faint sparking when you connect + to – of the battery.

Example: Short in a Series Circuit (1.21 Page-29)

Fuse/Circuit Breaker:

- A fuse is a replaceable safety device for an electrical circuit used when excessive current flow occurs in a conductor. It consists of a very thin piece of wire or a thin metal strip that is used to create an open circuit when too much current is flowing.
    - The wire has a quite low melting point. As current flows through the wire it heats up.
    - If **too large a current** flows, the wire or metal strip **melts;** thus **breaking** the circuit

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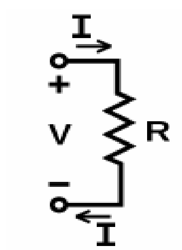
- Fuses are designed to work up to a certain amount of current (e.g. 1 amp, 15 amps, etc). When that maximum current is exceeded, then the wire within the fuse burns up from the heat of the current flow. With the fuse burnt up, there is now an "open circuit" and no more current flows.

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.
- Mathematically, 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.
- The law was named after the German physicist George Ohm.
- In circuit analysis, three equivalent expressions of Ohm's law are used interchangeably:

$$I = \frac{V}{R} \quad \text{or} \quad V = IR \quad \text{or} \quad R = \frac{V}{I}.$$

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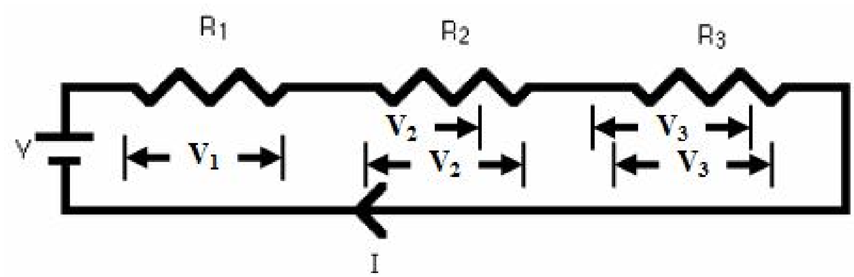
Equivalent Resistance

While in series:

- A series circuit is a circuit in which resistors are arranged in a chain, so the current has only one path to take.
- The total resistance of the circuit is found by simply adding up the resistance values of the individual resistors: equivalent resistance of resistors in series : $R=R_1+R_2+R_3$
- Source voltage in a series circuit divides proportionately across each resistor in the circuit.



Main Characteristics of a Series Circuit:

- Same current flows through all parts of the circuit. That is, the current is the same through each resistor.
- Voltage drop across each resistor is different due to its different value.
- Sum of the voltage drops across the resistors is equal to the voltage applied across the terminal. $V= V_1+ V_2+ V_3$
- Voltage drops are additive, $V= V_1+ V_2+ V_3$.
- Resistances are additive, $R=R_1+R_2+R_3$.
- Powers are additive, $P= P_1+ P_2+ P_3$

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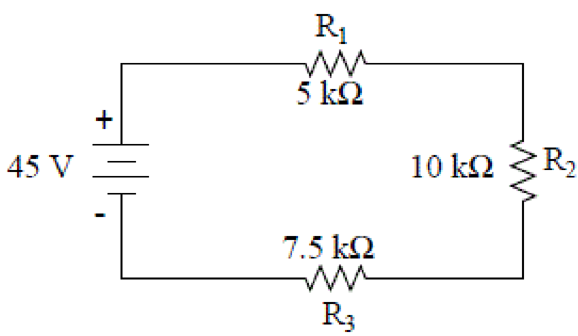
Division of Voltage in a Series Circuit: Using Voltage-Divider Rule

- A voltage divider circuit is a series network which is used to feed other networks with a number of different voltages and derived from a single input voltage source.
- Voltage drop across each resistor in a series circuit can be calculated according to Voltage Divider Rule, as:

  (i) Find equivalent resistance R of the series combination: $R=R_1+R_2+R_3$

  (ii) According to VDR, voltage drop across *n*th resistor is $V_n= V.\ R_n/R$



Example (Page-19): $V_2=V.\ R_2/R$; $V_3=V.\ R_3/R$ etc.

While in parallel:

- A parallel circuit is a circuit in which the resistors are arranged with their heads connected together, and their tails connected together.
- A parallel circuit has more than one current path connected to a common voltage source.
- The total resistance of a set of resistors in parallel is found by adding up the reciprocals of the resistance values, and then taking the reciprocal of the total: equivalent resistance of resistors in parallel, $1/R=1/R_1+1/R_2+1/R_3$
- The current in a parallel circuit breaks up, with some flowing along each parallel branch and re-combining when the branches meet again (the current adds up).

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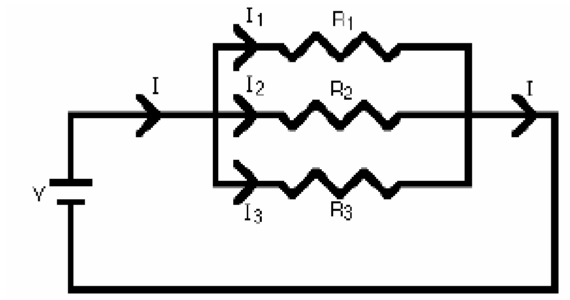
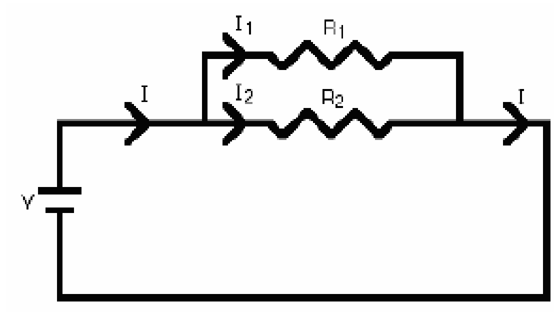


Division of Current for Two Resistors in Parallel: Using Current-Divider Rule



$$I_1 = I.\frac{R_2}{R_1 + R_2}$$

$$I_2 = I.\frac{R_1}{R_1 + R_2}$$

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In terms of conductance

$$I_1 = I.\frac{G_1}{G_1 + G_2}$$

$$I_2 = I.\frac{G_2}{G_1 + G_2}$$

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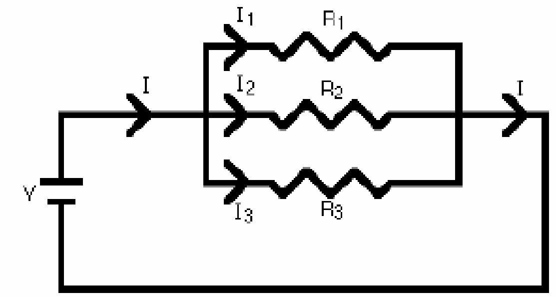
Division of Current for Three Resistors in Parallel: Using Current-Divider Rule



$$I_1 = I\left(\frac{R_2 R_3}{R_1 R_2 + R_2 R_3 + R_3 R_1}\right)$$

$$I_2 = I\left(\frac{R_1 R_3}{R_1 R_2 + R_2 R_3 + R_3 R_1}\right)$$

$$I_3 = I\left(\frac{R_1 R_2}{R_1 R_2 + R_2 R_3 + R_3 R_1}\right)$$

In terms of conductance

$$I_1 = I\left(\frac{G_1}{G_1 + G_2 + G_3}\right)$$

$$I_2 = I\left(\frac{G_2}{G_1 + G_2 + G_3}\right)$$

$$I_3 = I\left(\frac{G_3}{G_1 + G_2 + G_3}\right)$$

Main Characteristics of a Parallel Circuit:

- Potential difference across each resistance is the same as applied voltage.
- Current flowing in each resistor is different due to its different value.
- The sum of the currents flowing each resistor is the total current. $I=I_1+I_2+I_3$.
- Branch currents are additive, $I= I_1+ I_2+ I_3$.
- Conductance are additive, $G= G_1+ G_2+ G_3$
- Powers are additive, $P= P_1+ P_2+ P_3$.

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- If the resistors in parallel are identical, it can be very easy to work out the equivalent resistance.
  - In this case the equivalent resistance of N identical resistors is the resistance of one resistor divided by N, the number of resistors. So, two 40-ohm resistors in parallel are equivalent to one 20-ohm resistor; five 50-ohm resistors in parallel are equivalent to one 10-ohm resistor, etc.
- If you have two or more resistors in parallel, look for the one with the smallest resistance. The equivalent resistance will always be between the smallest resistance divided by the number of resistors, and the smallest resistance.
  - Here's an example. You have three resistors in parallel, with values 6 ohms, 9 ohms, and 18 ohms. The smallest resistance is 6 ohms, so the equivalent resistance must be between 2 ohms and 6 ohms (2 = 6/3, where 3 is the number of resistors). Doing the calculation gives 1/6 + 1/12 + 1/18 = 6/18. Flipping this upside down gives 18/6 = 3 ohms, which is certainly between 2 and 6.

While in series-parallel:

- Many circuits have a combination of series and parallel resistors.
- Generally, the total resistance in a circuit like this is found by reducing the different series and parallel combinations step-by step to end up with a single equivalent resistance for the circuit. This allows the current to be determined easily.
- The current flowing through each resistor can then be found by undoing the reduction process.
- General rules for doing the reduction process include:
  - Two (or more) resistors with their heads directly connected together and their tails directly connected together are in parallel, and they can be reduced to one resistor using the equivalent resistance equation for resistors in parallel.
  - Two resistors connected together so that the tail of one is connected to the head of the next, with no other path for the current to take along the line connecting them, are in series and can be reduced to one equivalent resistor.

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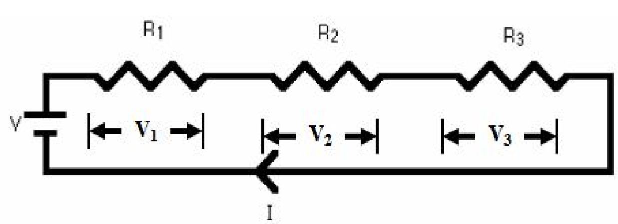
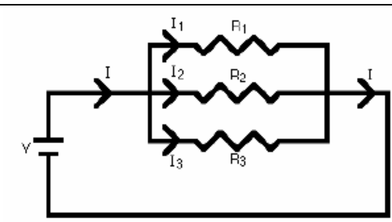
- Finally, remember that for resistors in series, the current is the same for each resistor, and for resistors in parallel, the voltage is the same for each one.

Duality between Series and Parallel Circuits:

- There is a certain peculiar pattern of relationship between series and parallel circuits.
- For example,
  - in a series circuit, current is the same whereas in a parallel circuit, voltage is the same.
  - in a series circuit, individual voltages across each resistor are added and in a parallel circuit, individual currents are added.
- It is seen that while comparing series and parallel circuits, voltage takes the place of current and the current takes the place of voltage. Such a pattern is known as duality and the two circuits are said to be duals of each other.
- Table below shows the equations involving voltage, current and resistance in a series circuit and corresponding dual counterparts in terms of current, voltage, and conductance for a parallel circuit.

Series Circuit	**Parallel Circuit**
	
$I_1 = I_2 = I_3 = I$	$V_1 = V_2 = V_3 = V$
$V = V_1 + V_2 + V_3$	$I = I_1 + I_2 + I_3$
$R = R_1 + R_2 + R_3$	$G = G_1 + G_2 + G_3$
$\frac{V_1}{R_1} = \frac{V_2}{R_2} = \frac{V_3}{R_3} = I$	$\frac{I_1}{G_1} = \frac{I_2}{G_2} = \frac{I_3}{G_3} = V$
Voltage Divider Rule: $V_1 = V.\frac{R_1}{R}$, $V_2 = V.\frac{R_2}{R}$, $V_3 = V.\frac{R_3}{R}$	Current Divider Rule: $I_1 = I.\frac{G_1}{G}$, $I_2 = I.\frac{G_2}{G}$, $I_3 = I.\frac{G_3}{G}$

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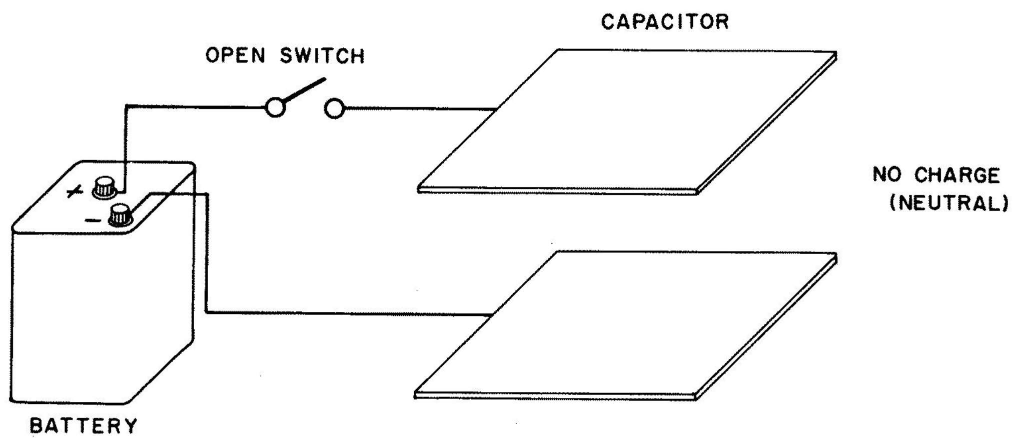
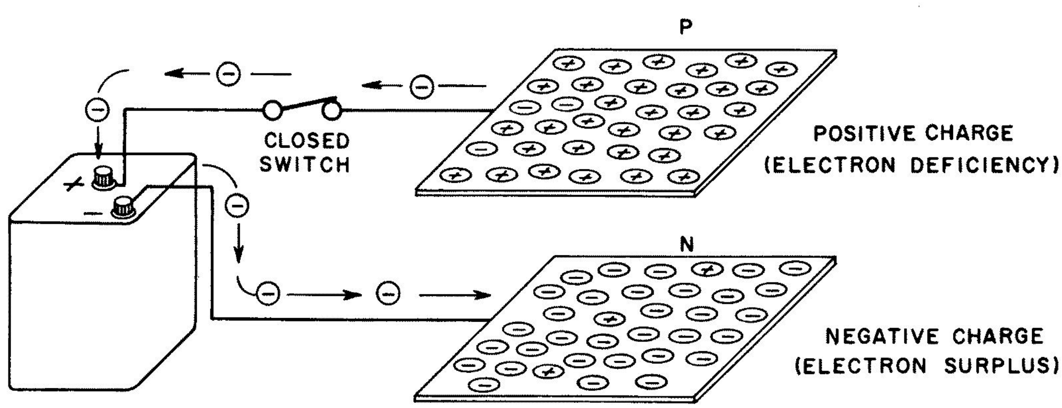
Capacitors

- The passive circuit element that that stores energy in an electric field is a capacitor.
- Over time, the capacitor may return the stored energy to the source or to another circuit element.
- A capacitor can retain charge after the removal of the source because the electric field can remain. (On the other hand, an inductor can not retain energy after the removal of the source because the magnetic field collapses).
- A capacitor essentially consists of two conducting surfaces separated by a layer of an insulating medium called dielectric.





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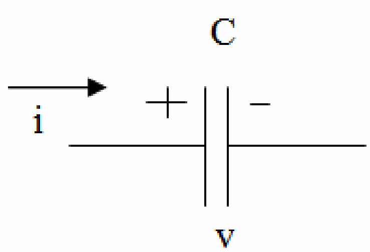
Capacitance:

- Capacitance is the property of a capacitor that store electricity.
- The capacitance of a capacitor may be defined as the amount of charge required to create a unit potential difference between its plates.
- Suppose, we give Q coulombs of charge to one of the two plates of a capacitor. If a potential difference of V volts is established between the two, then its capacitance is:

$$C=Q/V$$

- The symbol of capacitance is-



- Voltage drop across, current flowing through, and power in the capacitor are given by:

$$v = \frac{1}{c}\int i dt + k_1 \qquad i = C\frac{dv}{dt} \qquad P = vi = Cv\frac{dv}{dt}$$

- The energy stored in the electric field of capacitance is $w_C = \frac{1}{2}Cv^2$
- Basic unit of capacitance is the farad (f) or coulomb/volt.
- One farad is actually too large for practical purposes. Hence much smaller units like microfarad (μF), picofarad (pF) are generally used.

Types of Capacitors:

A few of the commonly used capacitors are as follows:

(i) Ceramic capacitors

(ii) Mica capacitors

(iii) Paper capacitors

(iv) Electrolytic capacitors

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Calculating Capacitance

While in series:

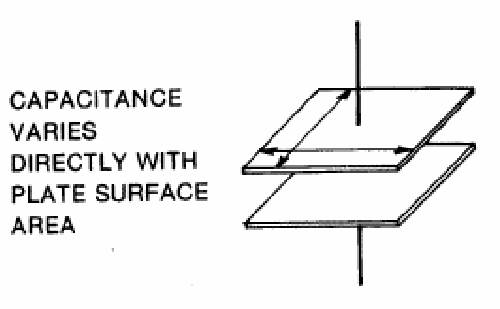
- 1/C=1/C1+1/C2+1/C3

While in parallel:

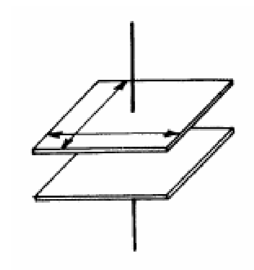
- C=C1+C2+C3

Parameters or Variables determining capacitance:

- Capacitance is determined by 3 factors:
  - » plate surface area
  - » plate spacing
  - » insulating material (dielectric)
- Parallel capacitors increase plate area; so increase charge and hence increase capacitance.
- Series capacitors decrease plate area; so decrease charge and hence decrease capacitance.



HIGH CAPACITANCE



LOW CAPACITANCE

Lecture-02: Basic Circuit Elements

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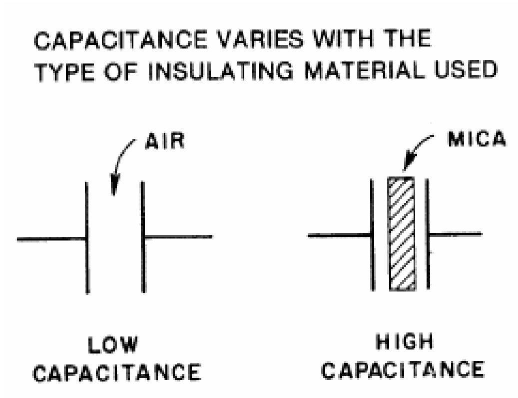
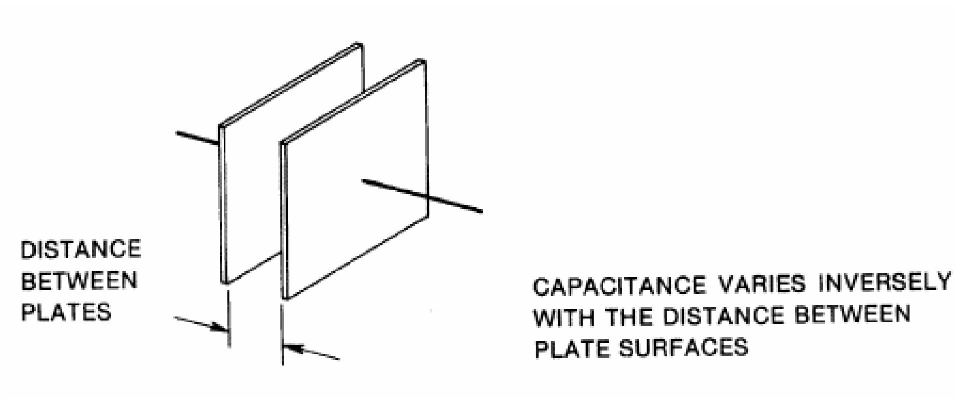


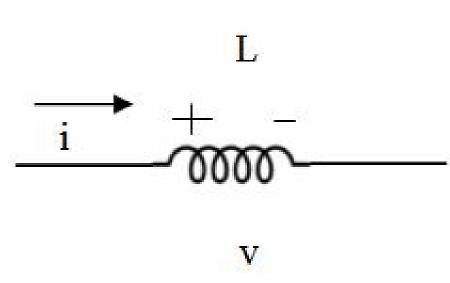


Inductors

- There are two fundamental principles of electromagnetics:
    1. Moving electrons create a magnetic field.
    2. Moving or changing magnetic fields cause electrons to move.
- An inductor is a coil of wire through which electrons move, and energy is stored in the resulting magnetic field.
- Like capacitors, inductors temporarily store energy.
- An inductor can not retain energy after removal of the source, because the magnetic field collapses.
- Unlike capacitors:
    - Inductors store energy in a magnetic field, not an electric field.

- The magnetic field is proportional to the current. When the current drops to zero, the magnetic field also goes to zero.

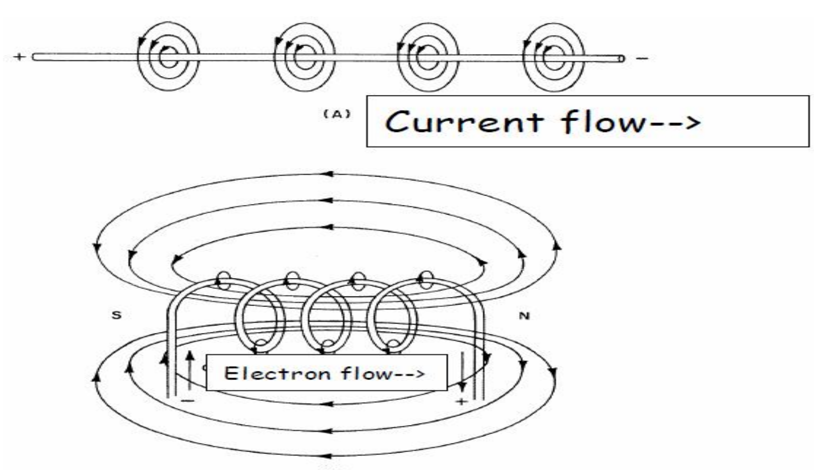
- Basic unit of inductance is the henry (h).
- Alphabetically, it is expressed as L.
- The symbol of inductance is-



- Voltage drop across, current flowing through, and power in the inductor are given by:

$$v = L\frac{di}{dt} \qquad i = \frac{1}{L}\int vdt + k_1 \qquad P = vi = L\frac{di}{dt}$$

- The energy stored in the magnetic field of an inductor is $w_L = \frac{1}{2}Li^2$
- The rate at which current through an inductor changes is proportional to the voltage across it.
- A coil (or inductor) has a property called its inductance. The larger the inductance, slower the rate at which the current changes.



Lecture-02: Basic Circuit Elements

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Note:

- Current flows from + to -, but is carried by electrons which flow from - to +.

Calculating Inductance

While in series:

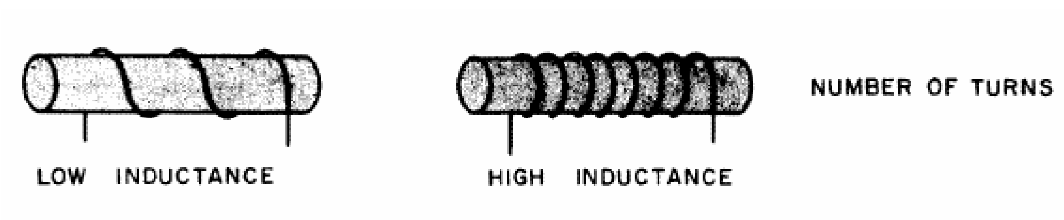
- L=L1+L2+L3

While in parallel:

- 1/L=1/L1+1/L2+1/L3

Parameters or Variables determining inductance:

- Inductance (L) of a coil is influenced by 4 factors:
  - » number of turns of the coil
  - » permeability of the core
  - » cross sectional area of the core
  - » spacing of the turns
  - » diameter of the coil
  - » spacing between turns
  - » size of the wire used
  - » type of material used inside the coil



Lecture-02: Basic Circuit Elements

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