IDC102:Hands-on Electronics
Lecture – 3

Resistivity, Resistance and Resistor

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Acknowledgment:

- *Several contents and materials are collected from google search (mostly picture) and lectures available in internet, the actual one-to-one origins are lost as these are done over several years of my learning and making of slides. Some sentences are kept exactly same as of source as they look beautiful.*

- However, I have taken several materials from following sources:
  - Dr. Samsun M. BAŞARICI,
  - Animated Science,
  - Teachers Lab Group CERN,
  - NTU and KT Oscilloscope Simulation,
  - M. Tonapi, Clemson University
  - J. Schwartz (New York, NY, USA)
  - Google.com
  - *Hawkins Electrical Guide, Volume 6, 1917.*

Books:

Hands-On Electronics: A Practical Introduction to Analog and Digital Circuits, by Daniel M. Kaplan and Christophore G. White

Electronics devices and circuit theory, 09th edition, Prentice Hall (2005). By R. L. Boylestad and L. Nashelsky,

Components on a board.

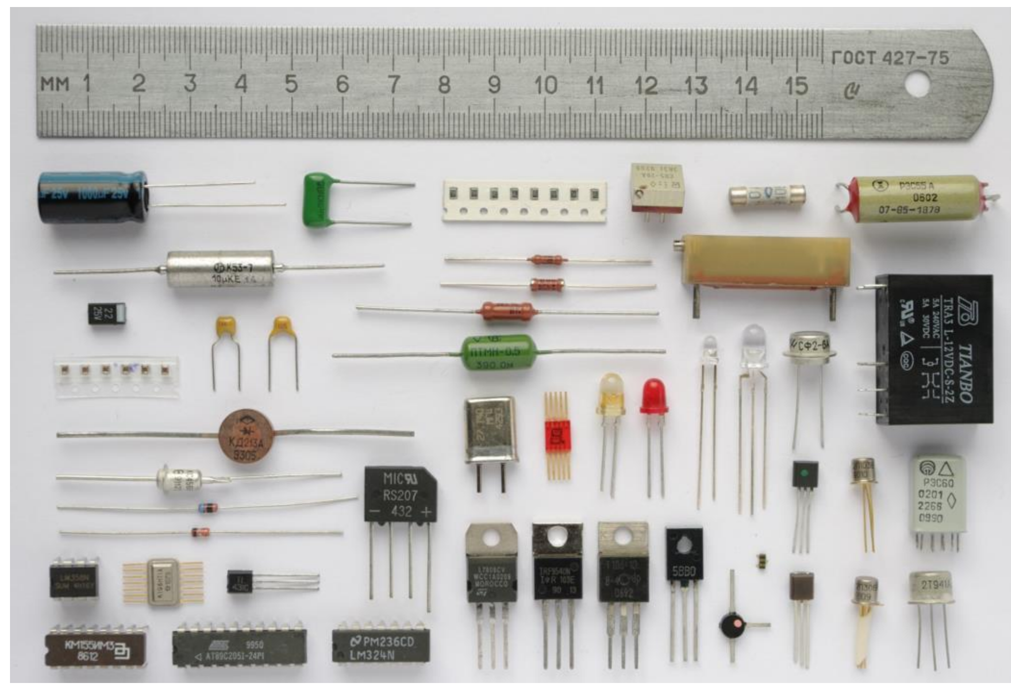
Components

An electronic component is any physical entity in an electronic system used to affect the electrons or their associated fields in a manner consistent with the intended function of the electronic system.

Components are generally intended to be connected together, usually by being soldered to a printed circuit board (PCB), to create an electronic circuit with a particular function (for example an amplifier, radio receiver, or oscillator).

Components may be packaged singly, or in more complex groups as integrated circuits. Some common electronic components are capacitors, inductors, resistors, diodes, transistors, etc. Components are often categorized as active (e.g. transistors and thyristors) or passive

Each discrete component has a specific symbol when represented on a schematic diagram.



Components

- There are two types of components: *passive components and active components.*
- Passive Components :

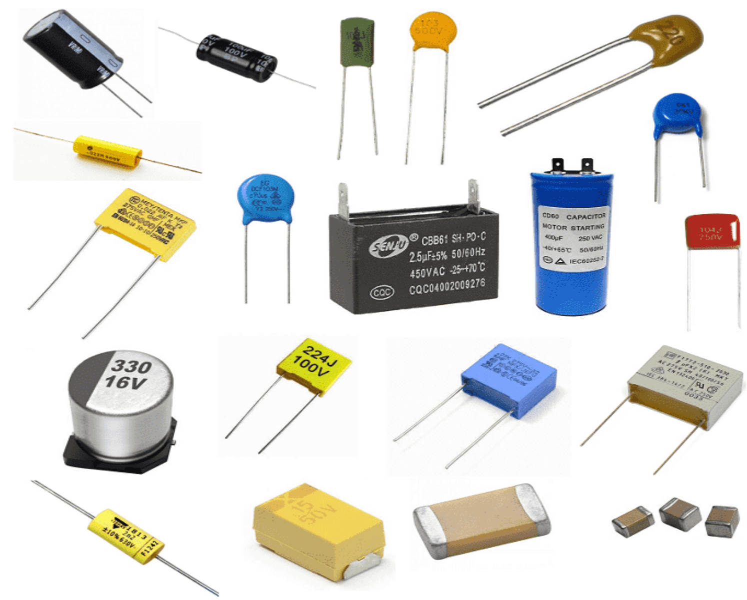
A passive device is one that contributes no power gain (amplification) to a circuit or system. It has no control action and does not require any input other than a signal to perform its function. Since passive components always have a gain less than one, they cannot oscillate or amplify a signal. A combination of passive components can multiply a signal by values less than one; they can shift the phase of a signal, reject a signal because it is not made up of the correct frequencies, and control complex circuits, but they cannot multiply by more than one because they basically lack gain. Passive devices include resistors, capacitors and inductors.

- Active Components:

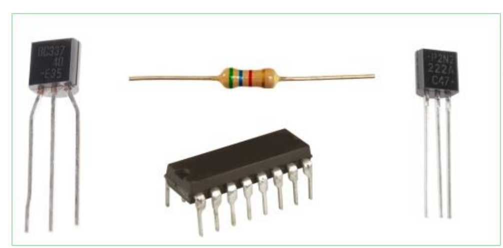
Active components are devices that are capable of controlling voltages or currents and can create a switching action in the circuit. They can amplify or interpret a signal. They include diodes, transistors and integrated circuits. They are usually semiconductor devices.

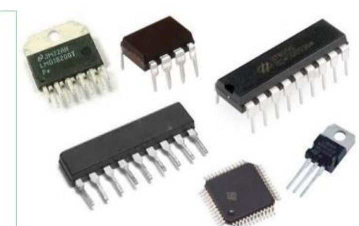
Discrete and Integrated

- When a component is packaged with one or two functional elements, it is known as a *discrete* component.
  - For example, a resistor used to limit the current passing through it functions as a discrete component.



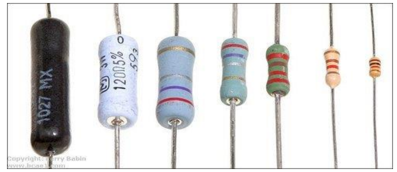
- On the other hand, an *integrated circuit is a combination of several interconnected* discrete components packaged in a single case to perform multiple functions.
  - A typical example of an integrated circuit is that of a microprocessor which can be used for a variety of applications.



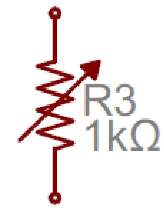


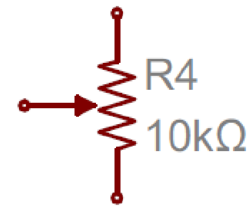
Components

Resistor

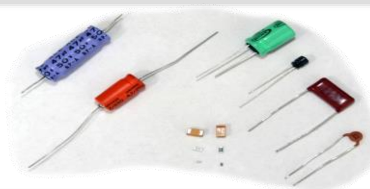


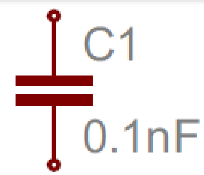
Variable Resistor

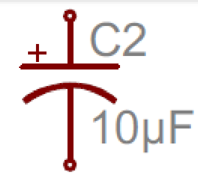




Capacitors

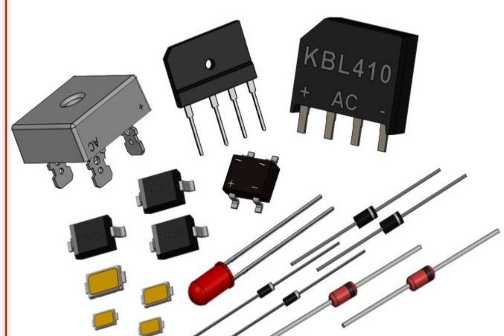


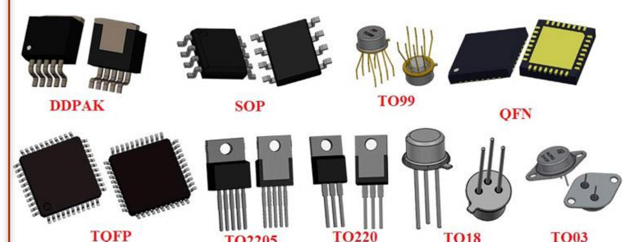




Inductors

Diodes

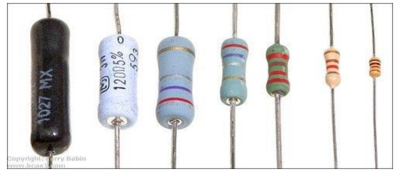


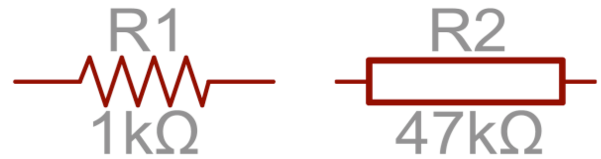


Transistor and IC

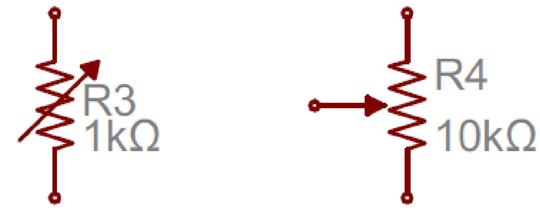
Components

Resistor

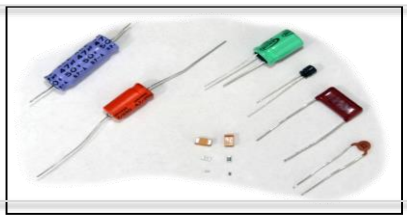


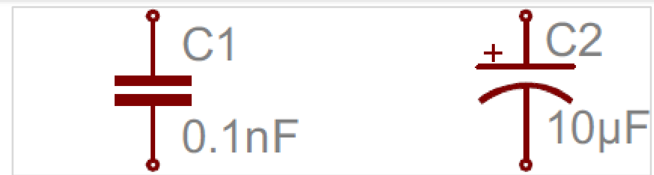


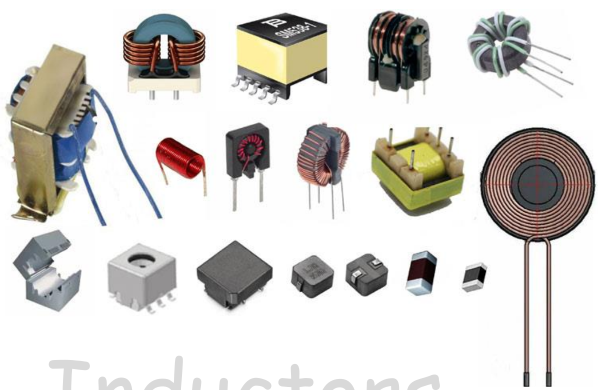
Variable Resistor



Capacitors

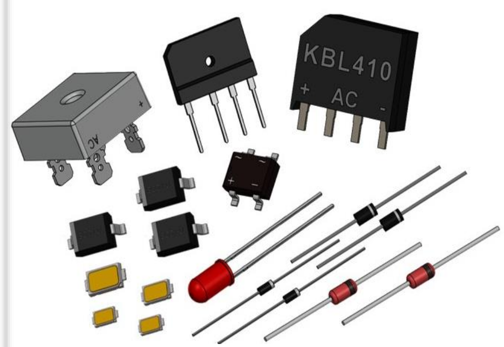


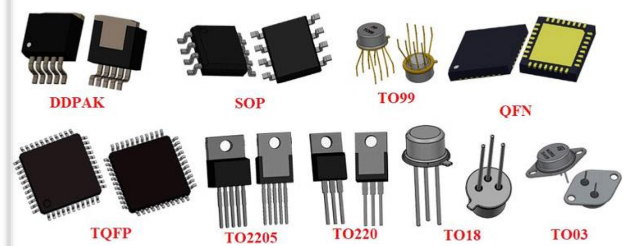




Inductors

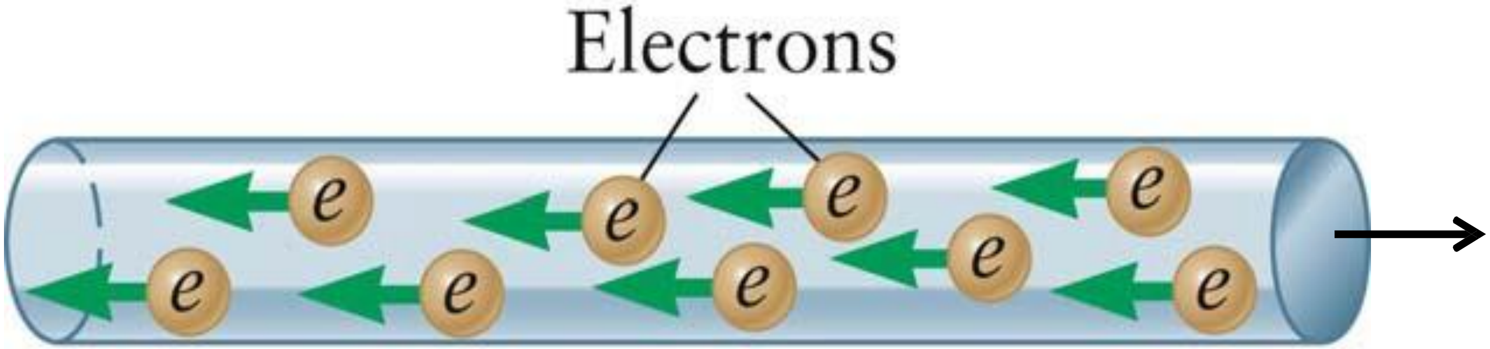
Diodes



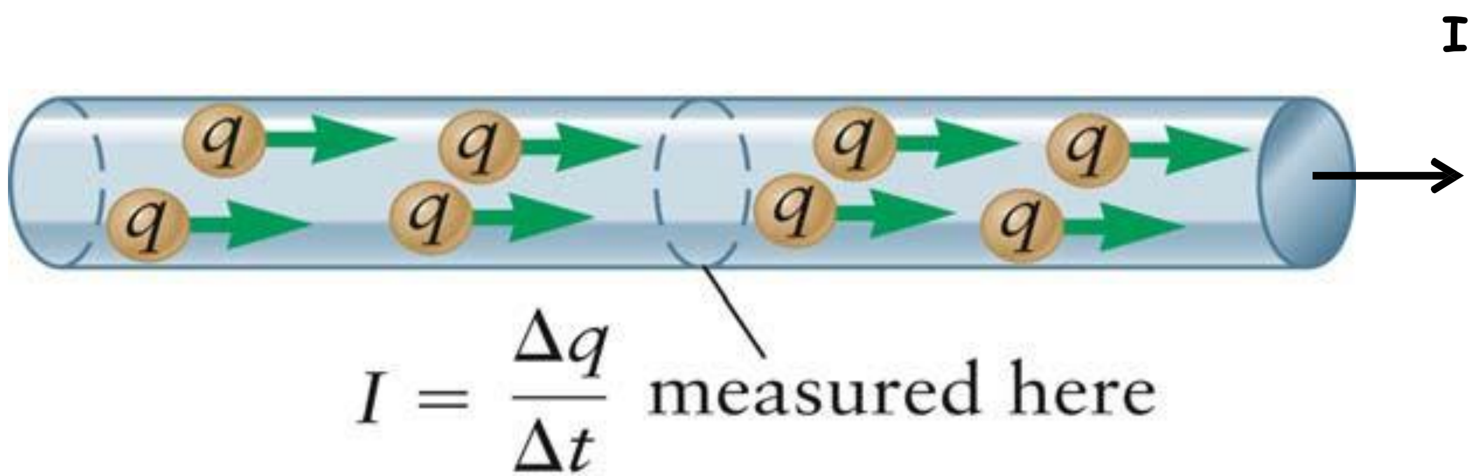


Transistor and IC

When current flows through a wire

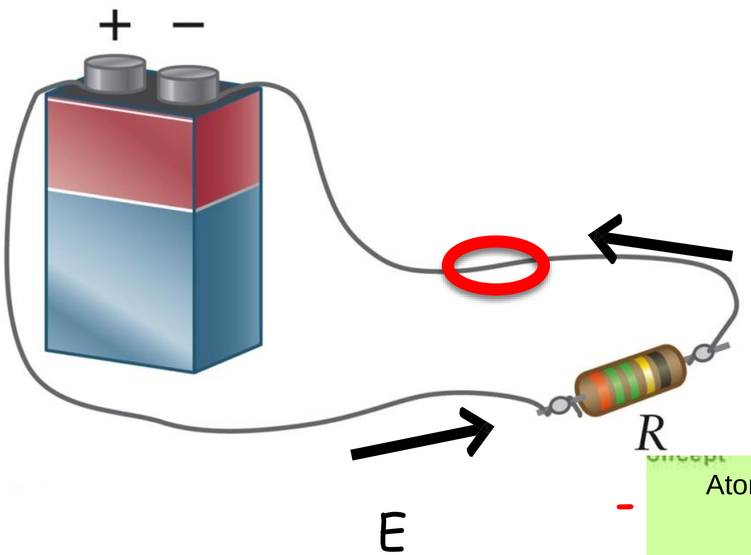


Definition of Conventional Current



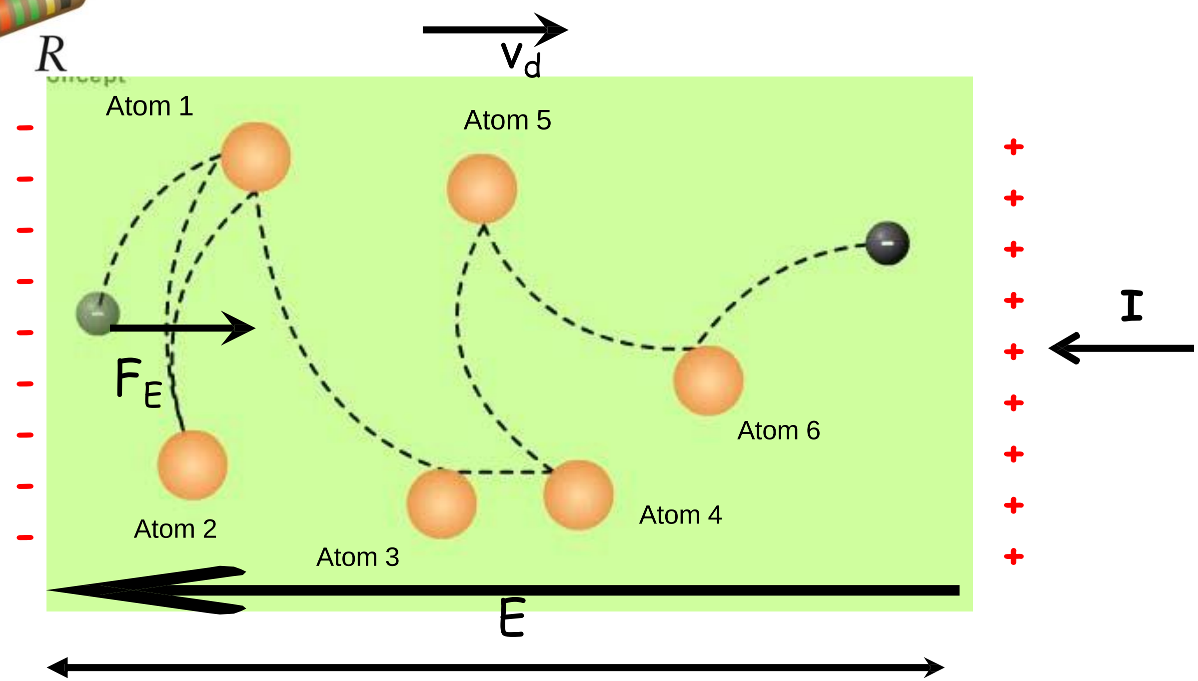
By definition, the direction of current flow for either case is the same.

Microscopically, how does the current flow in a wire?



Net drift velocity of electron due to applied electric field

$$E = -\Delta V / \Delta s$$



A few nanometers (1 nm = 1×10^{-9} m)

Current and Drift Velocity

- Current is related to the drift velocity

$$v_d = -\frac{I}{neA}$$

where: A= wire cross section, n= number density of electrons, I=current

- For a household size copper wire carrying 1 A of current, the drift velocity is about 0.01 m/s!
- There is no perceptible time delay between when you push a switch and when the light comes on
- The speed of the electric current is equal to the speed of electromagnetic radiation in the wire
  - This is nearly the speed of light

ELECTRICAL PROPERTIES

- Within metals, electrical charge is transported by the "free electrons".
- The parameters determining the electrical conductivity of metals are:

  N: the number of electrons per unit volume

  e: the charge carried by an electron

  m: the mass of an electron

  v: the average velocity of "conduction electrons"

  ℓ_e : the average distance the electrons travel before being scattered by atomic lattice perturbation (the mean free path)
- Only the mean free path ℓ_e is temperature dependant. At high (ambient) temperature, the electron free path ℓ_e is dominated by electron scattering from thermal vibrations (phonons) of the crystal lattice. The electrical conductivity is linearly temperature-dependant.
- At low temperature, the free path ℓ_e is limited mainly by scattering off chemical and physical crystal lattice imperfections (impurities, vacancies, dislocations). The electrical conductivity tends to a constant value.

Electrical Resistivity (ρ)

Some materials, like metals, offer little resistance to current flow. Other materials, like plastic, offers high resistance to current flow. *Resistivity* is used to quantify how much a given material resists the flow of current. The electrical resistivity is measured in Ohm.m Its inverse is the conductivity measured in S/m

$$\sigma = \frac{1}{\rho}$$

$$\rho = \frac{m_e v_F}{ne^2 \ell} = \frac{m_e}{ne^2\ \tau}$$

n: the number of electrons per unit volume

e: the charge carried by an electron

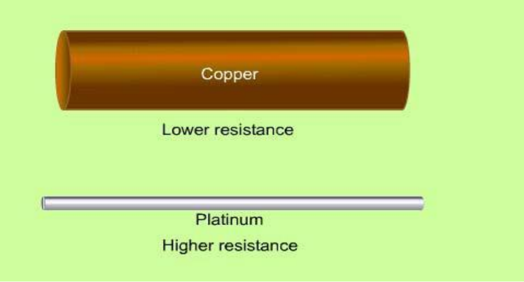
m_e: the mass of an electron

v_F: the average velocity of "conduction electrons"

ℓ : the average distance the electrons travel before being scattered by atomic lattice perturbation (the mean free path)

Lower Resistivity → Better Conductor

- Resistivity is a property of a material.
- Resistance of a component depends on BOTH geometry as well as the resistivity of the material from which it is made.

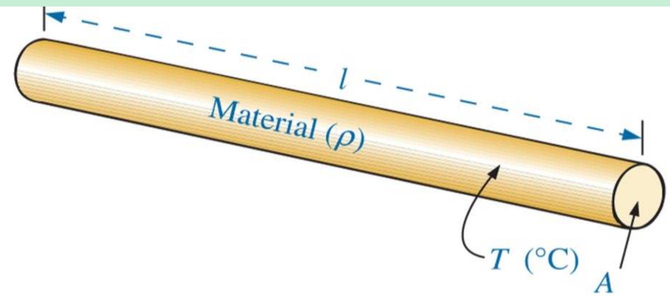


Resistance (R)

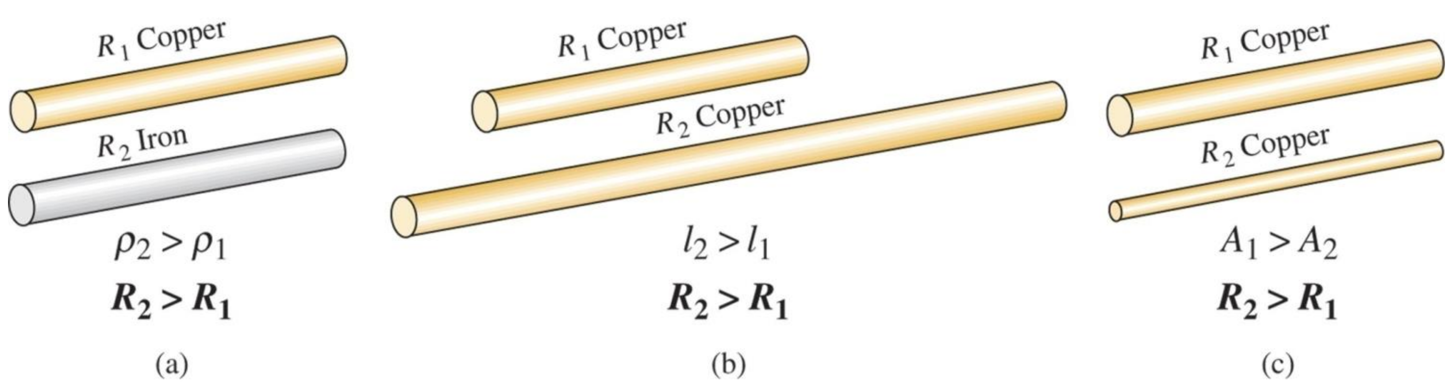
- Resistance is the opposition a material offers to current.
- Resistance (R) of an element denotes its ability to resist the flow of electric current.

Resistance is determined by:

- Type of material (resistivity) (ρ)
- Cross-sectional area (A)
- Temperature of material
- Length of material (l)



- The higher the resistivity of a conductor, the higher its resistance.
- The longer the length of a conductor, the higher its resistance.
- The lower the cross-sectional area of a conductor, the higher its resistance.
- The higher the temperature of a conductor, the higher its resistance.



Resistance Terminology

Quantity is RESISTANCE (R)

Base Unit is OHM (Ω)

An ohm equals a volt per ampere.

Example of usage:

Resistance = 14 ohm

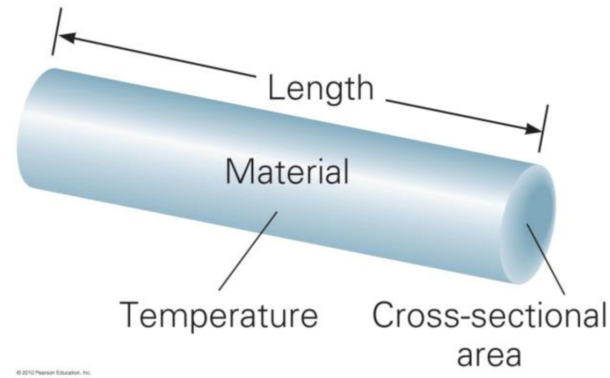
R = 14 Ω

One ohm (1 Ω) is the resistance if one ampere (1 A) is in a material when one volt (1 V) is applied.

Conductance is the reciprocal of resistance. $G = \frac{1}{R}$

On what will a wire's resistance depend?

- There are 4 primary factors when determining a wire's resistance:
  - Material composition
  - Length of the wire
  - Cross-sectional Area of the wire
  - Temperature



$$R = \frac{\rho \times length}{section}$$

$$\sigma = \frac{1}{\rho}$$

Electrical Resistivity =

$$\rho = \frac{m_e v_F}{ne^2 \ell} = \frac{m_e}{ne^2\ \tau}$$

n: the number of electrons per unit volume

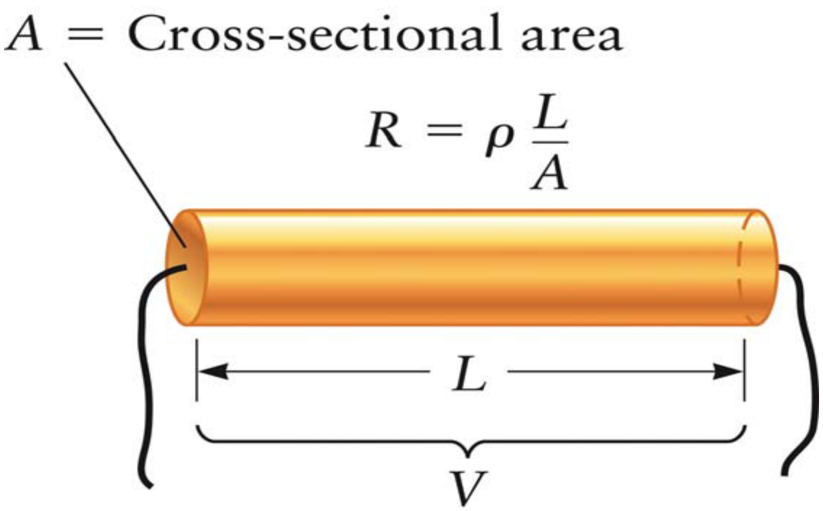
e: the charge carried by an electron

m_e: the mass of an electron

v_F: the average velocity of "conduction electrons"

ℓ: the average distance the electrons travel before being scattered by atomic lattice perturbation (the mean free path)

What determines resistance R for a wire?



Units: L (m); A(m²); $\rho(\Omega \cdot m)$; $R(\Omega)$

Some materials, like metals, offer little resistance to current flow. Other materials, like plastic, offers high resistance to current flow.

Resistivity is used to quantify how much a given material resists the flow of current.

Resistivity is a property of a material.

$$R \propto \frac{L}{A}$$

RESISTIVITIES $(\Omega \cdot m)$, at 20° C

Conductors	
Silver	1.6×10^{-8}
Copper	1.7×10^{-8}
Aluminum	2.7×10^{-8}
Iron	9.6×10^{-8}
Platinum	10.5×10^{-8}
Nichrome	107.5×10^{-8}

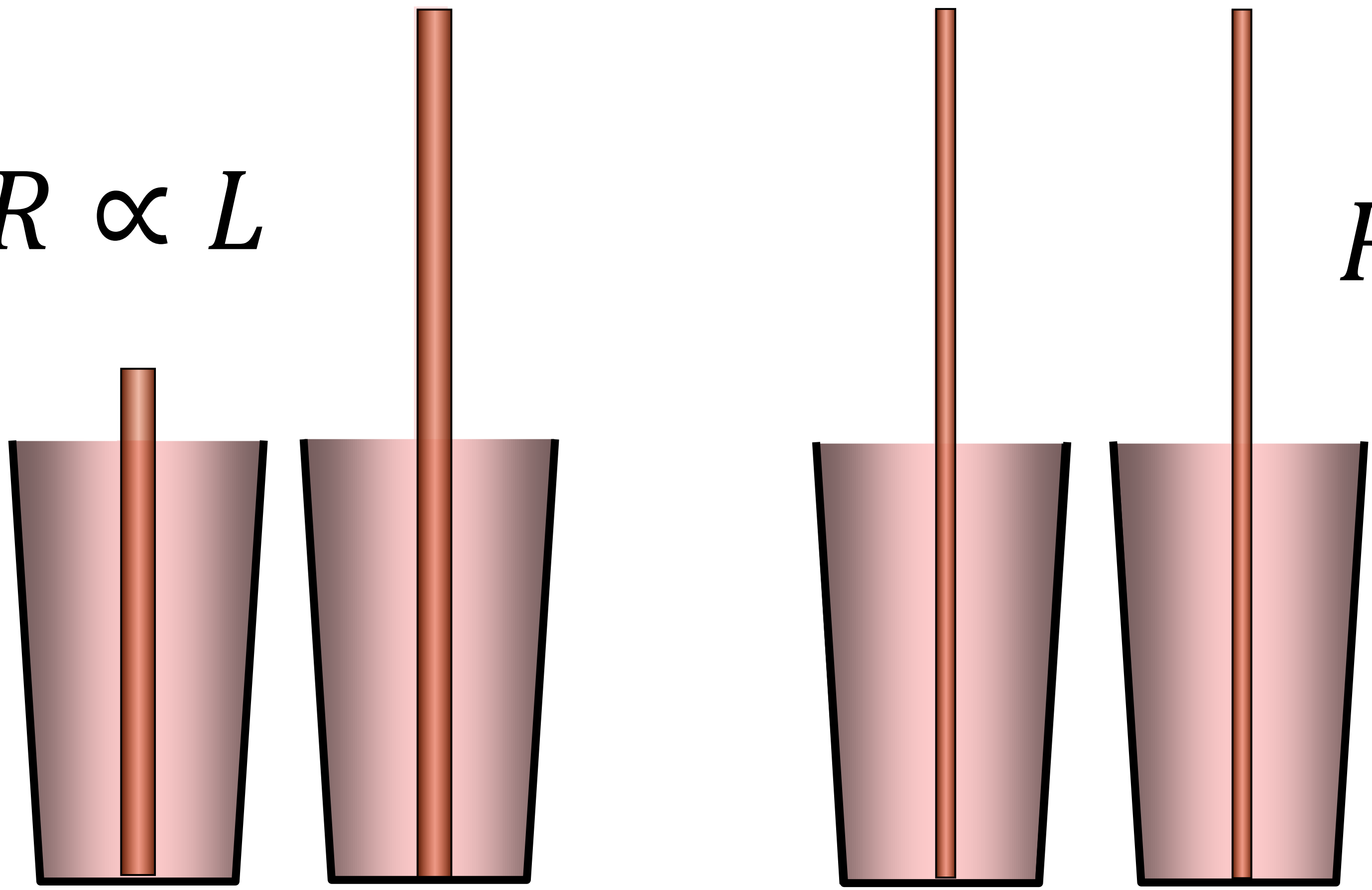
Semi-conductors	
Carbon	3.5×10^{-5}
Silicon	2.5×10^{3}

Insulators	
Glass	10^{10} - 10^{14}
Rubber	1.0×10^{13}

On what will a wire's resistance depend?

Imagine that you are testing the resistance of a straw while drinking a milkshake...

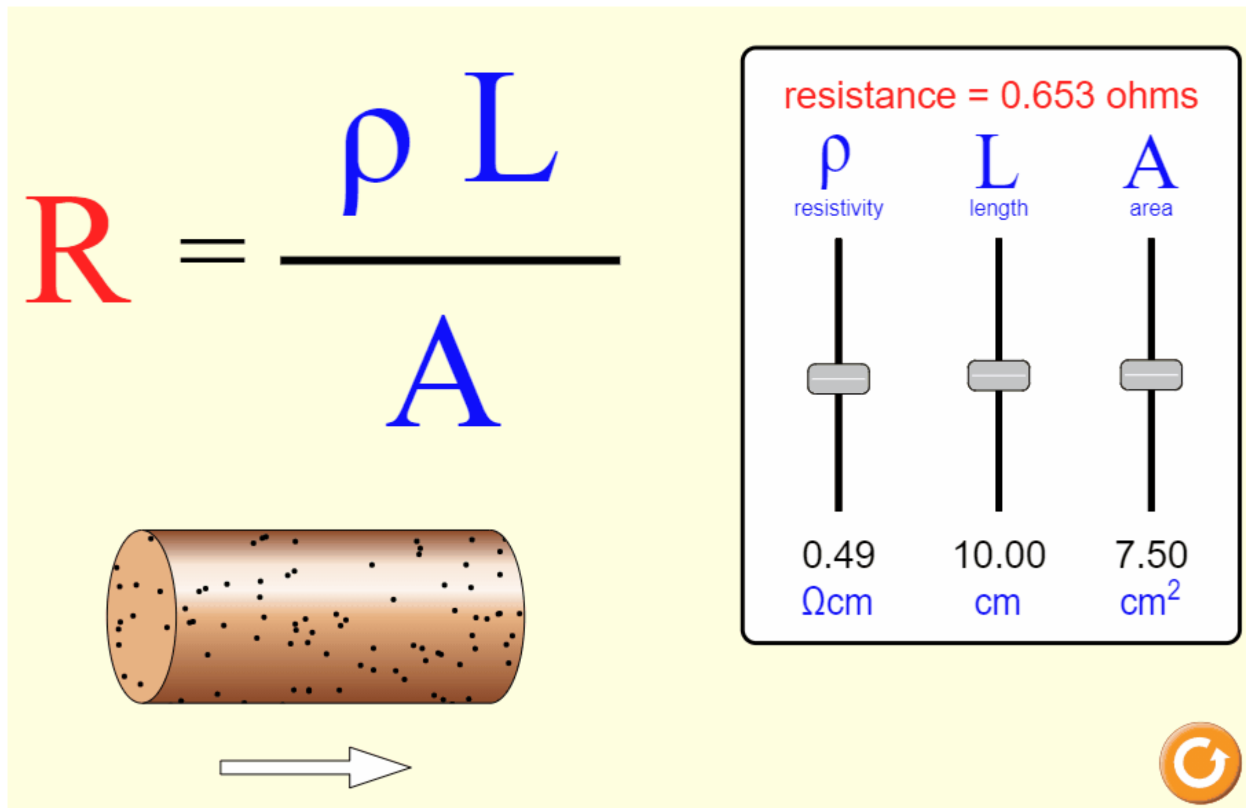
$$R \propto L$$



$$R \propto \frac{1}{A}$$

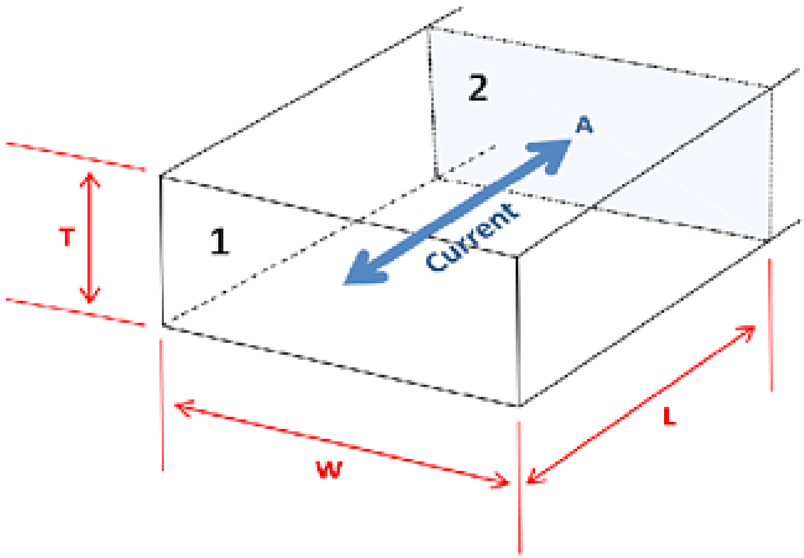
What factors affect the resistance of a wire?

- Cross-sectional Area
- Length
- Material



sheet resistance

$$R = RESISTANCE = \frac{\rho \cdot L}{A} \ (Units : \Omega \ (Ohms))$$



A = T x W

For a Square L = W, so A = T x L

and

$$R_{Square} = \frac{\rho \cdot L}{T \cdot L} = \frac{\rho}{T} \quad (Units : \ \Omega / Square)$$

Resistivity: Example

- To summarize: for a given material (say, copper) the resistance of a piece of uniform wire is proportional to its length ℓ and inversely proportional to its cross-sectional area A.

$$R = \rho \frac{L}{A}$$

$$R = \frac{\rho L}{A} = \frac{L}{\sigma A}$$

L = length

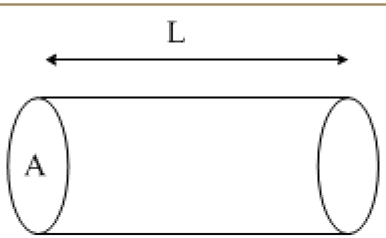
A = cross-sectional area

ρ = resistivity of material

σ = conductivity of material

Example: Find the resistance of a 2-m copper wire if the wire has a diameter of 2 mm.

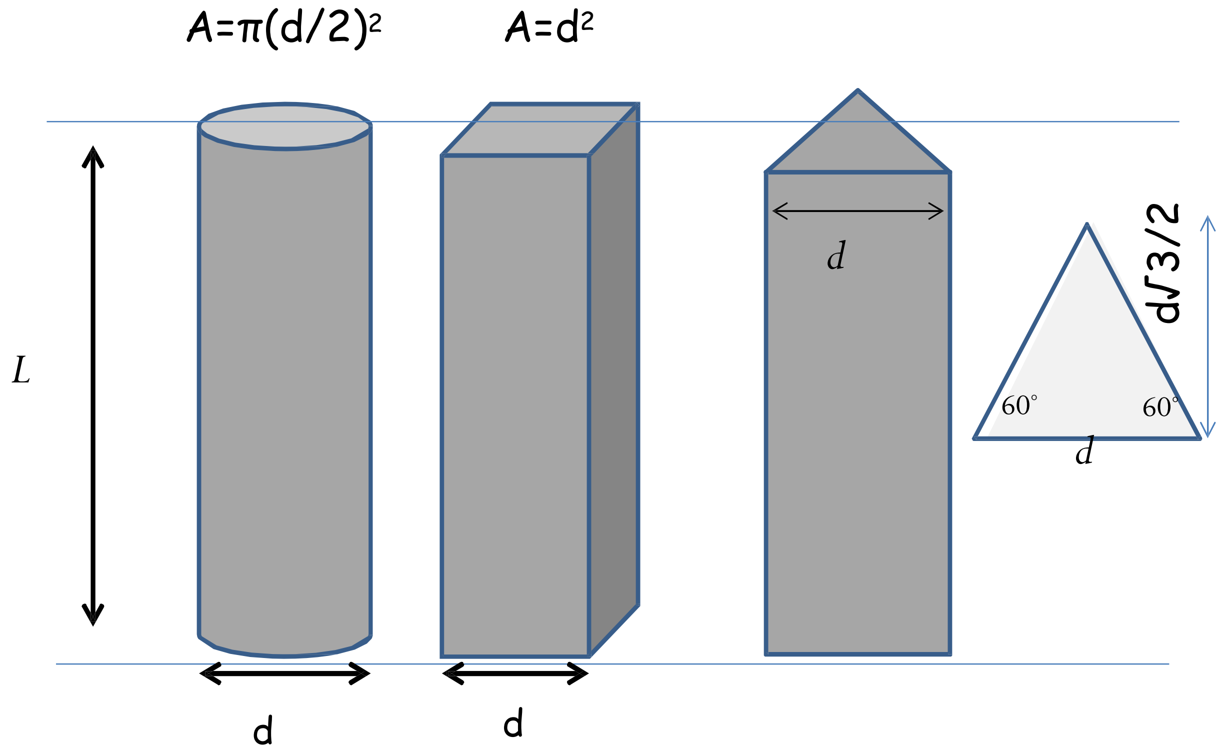
$$\rho_{Cu} = 2\times 10^{-8}\,\Omega\cdot\mathrm{m}$$

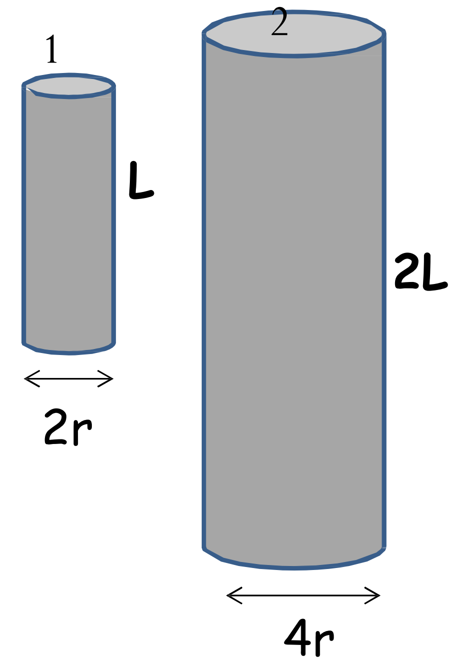


$$A = \pi r^2 = \pi(0.001)^2$$

$$R = \frac{\rho L}{A} = \frac{(2\times10^{-8}\,\Omega\cdot\mathrm{m})(2\mathrm{m})}{\pi(0.001)^2\,\mathrm{m}^2} = 1.273\times10^{-2}\,\Omega = 12.73\ \mathrm{m}\Omega$$

Three wires, same length & material different cross-sections





$$R=\rho\frac{4L}{\pi d^2}=1.273\,\frac{\rho L}{d^2}$$

$$R=\rho\frac{L}{d^2}=\frac{\rho L}{d^2}$$

$$R=\rho\frac{4L}{\sqrt{3}d^2}=2.309\,\frac{\rho L}{d^2}$$

$$R=\rho\frac{L}{\pi r^2}$$

$$R_2=\rho\frac{2L}{\pi(2r)^2}=\rho\frac{2L}{4\pi(r)^2}$$

$$=\rho\frac{L}{2\pi(r)^2}=\frac{R}{2}$$

American Wire Gauge (AWG)

Determine the resistance of a 100 meter length of 12 AWG (2.052 mm diameter) solid wire made of the following materials:

a.copper (resistivity = $1.67\times10^{-8}\ \Omega\cdot m$):

b.aluminum (resistivity = $2.65\times10^{-8}\ \Omega\cdot m$)

c.iron (resistivity = $9.71\times10^{-8}\ \Omega\cdot m$)

Can a copper wire and an aluminum wire of the same length have the same resistance?

$$\text{Area} = \pi R^2 = \pi\,(0.002052\text{m}/2)^2 = 3.31 \times 10^{-6}\ \text{m}^2$$

$$R_{Copper} = \rho_{Cu} L/A = (1.67 \times 10^{-8}\ \Omega\ \text{m})\ 100\text{m}/(3.31 \times 10^{-6}\ \text{m}^2) = 0.504\ \Omega$$

$$R_{Aluminun} = \rho_{Al} L/A = (2.65 \times 10^{-8}\ \Omega\ \text{m})\ 100\text{m}/(3.31 \times 10^{-6}\ \text{m}^2) = 0.801\ \Omega$$

$$R_{iron} = \rho_{Fe} L/A = (9.71 \times 10^{-8}\ \Omega\ \text{m})\ 100\text{m}/(3.31 \times 10^{-6}\ \text{m}^2) = 2.93\ \Omega$$

Resistivity – Example #1

Conductor Material	Resistivity (Ohm meters @ 20 °C)
Silver	1.64×10^{-8}
Copper	1.72×10^{-8}
Aluminum	2.83×10^{-8}
Tungsten	5.50×10^{-8}
Nickel	7.80×10^{-8}
Iron	12.0×10^{-8}
Constantan	49.0×10^{-8}
Nichrome II	110×10^{-8}

Calculate the resistance of a 1.8 m length of iron wire of with a diameter of 3 mm

$$R = (12.0 \times 10^{-8}) \frac{(1.8)}{(7.07 \times 10^{-6})}$$

$$\boxed{R = \rho \frac{L}{A}}$$

$L = 1.8$ m

$\rho = 12.0 \times 10^{-8}$ Ωm

$$\boxed{R = 0.0306\ \Omega}$$

$A = \pi(0.003/2)^2 = 7.07 \times 10^{-6}$ m^2

Resistivity - Example #2

A current of 4 A flowed through a 75 m length of metal alloy wire of area 2.4 mm^2 when a p.d. of 12 V was applied across its ends. What was the resistivity of the alloy?

$$\boxed{\rho = \frac{RA}{L}}$$

$$R = \frac{V}{I} = \frac{12}{4} = 3\ \Omega$$

$$L = 75\ \text{m}$$

$$A = 2.4\ \cancel{\text{mm}^2} \times \left(\frac{1\ \text{m}}{1000\ \cancel{\text{mm}}}\right)^2$$

$$A = 2.4 \times 10^{-6}\ \text{m}^2$$

$$\rho = \frac{(3)(2.4 \times 10^{-6})}{(75)}$$

$$= \mathbf{9.6 \times 10^{-8}\ \Omega m}$$

Resistivity - Example #3

$$\textbf{Resistance} = \frac{\text{Resistivity x length}}{\text{area}}$$

$$R = \frac{\rho\, l}{A}$$

Example:

$$R = \frac{\rho\, l}{A} = \frac{1.4 \times 10^{-6}\ \Omega\cdot\text{cm} \ \ \text{x} \ \ 2 \times 10^{4}\ \text{cm}}{0.28\ \text{cm}^2}$$

$$= 0.1\ \Omega$$

Temperature Dependence of Resistivity

- Resistivity of metals increases approximately linearly with temperature over a wide range.

- The formula is:

$$\rho_T = \rho_0\left[1+\alpha\left(T-T_0\right)\right]$$

ρ_0 being the resistance at some fixed T_0, and α the temperature coefficient of resistivity.

- An old incandescent (not LED) bulb has a tungsten wire at about 3300K, and $\alpha = 0.0045$, from which $\rho_T = 15\rho_0$ not far off proportional to temperature.

Resistance: Temperature Effect

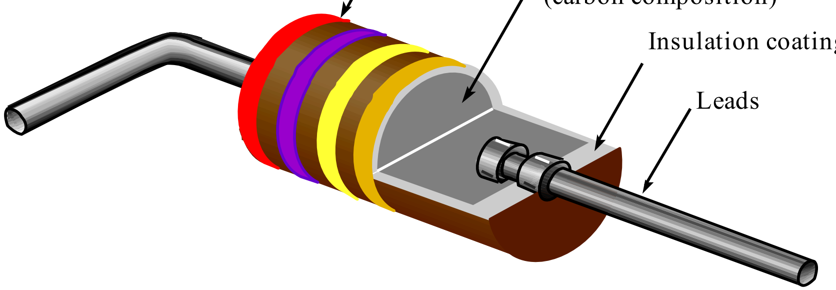
- Temperature have a significant effect on the resistance of conductors, semiconductors and insulators.
- Conductors
  - ***For good conductors, an increase in temperature will result in an increase in the resistance level. Consequently conductors have a positive temperature coefficient.***
- Semiconductor
  - ***For semiconductor materials, an increase in temperature will result in a decrease in the resistance level. Consequently, semiconductors have negative temperature coefficient.***
- Insulators = Semiconductors

- For a moderate range of temperature, such as 100°C, the change of resistance is usually proportional to the change of temperature;
- The ratio of the change of resistance per degree change of temperature to the resistance of some definite temperature are called coefficient of resistance, α.

A device out of this properties

- Thus, a material or a device which can impede current flow, causing a voltage drop when placed in an electrical circuit is called resistor.

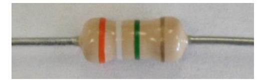
Components designed to have a specific amount of resistance are called *resistors*.



- Both alternating and direct currents are impeded by perfect resistors.

- Let's see about Resistor In more detail.

Resistors



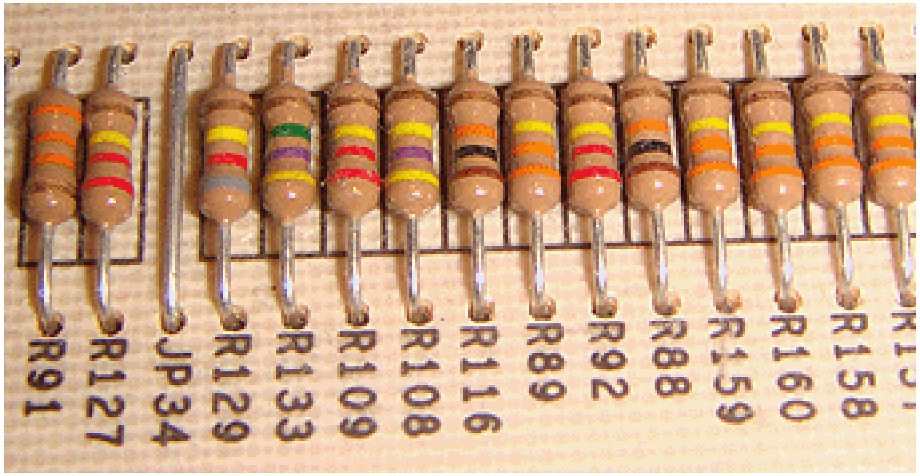
- A resistor is an electronic component that resists the flow of electrical current. => A resistor is typically used to control the amount of current that is flowing in a circuit.

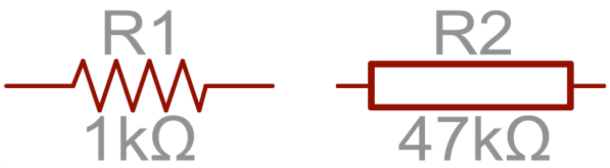
- A resistor is a **passive** component, it does not require a power supply to operate, the resistance is a property of the material that the resistor is made from.

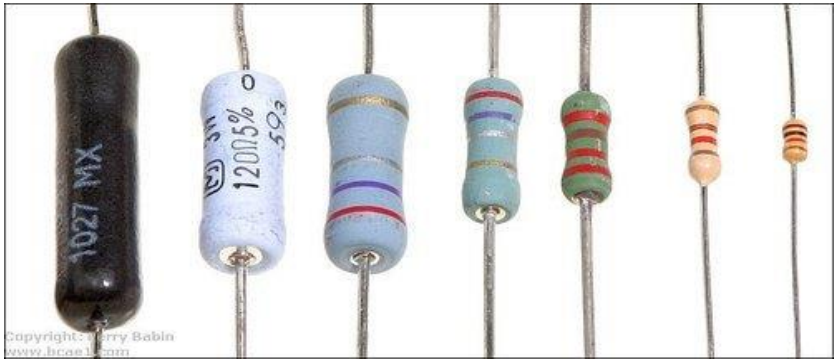
- When current flows through a resistor, it dissipates **energy** and gets **hot** - this may or may not be useful! All resistors have a maximum power rating which, if exceeded, results

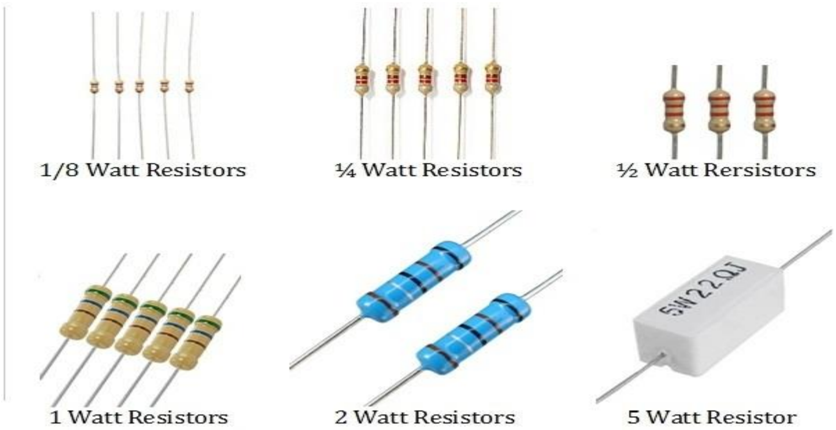
- Resistance is measured in units of ohms (Ω) and named after George Ohm, whose law (Ohm's Law) defines the fundamental relationship between voltage, current, and resistance. And all resistors have a **tolerance** that indicates how close they actually are to the stated value of resistance

Resistor





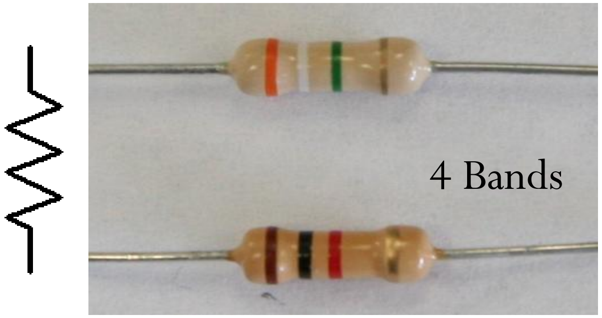




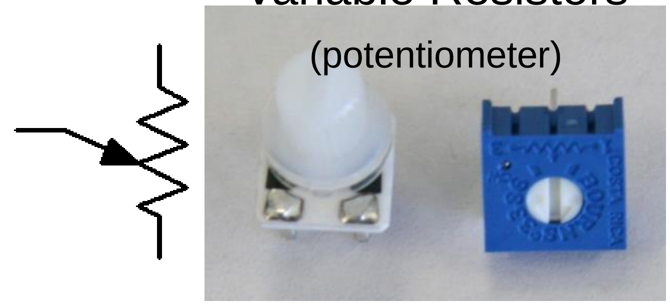
- Opposition to the flow of current is termed **resistance.**
- The fact that a wire can become hot from the flow of current is evidence of resistance.
- Conductors have very little resistance.
- Insulators have large amounts of resistance.

Resistors: Types and Package Styles

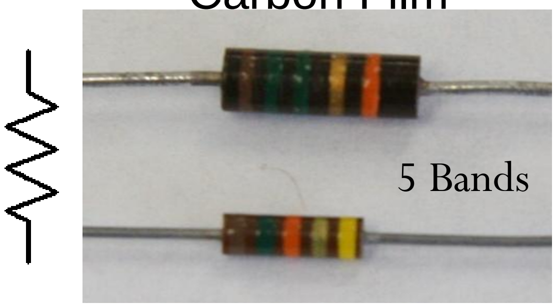
Carbon Film Resistors



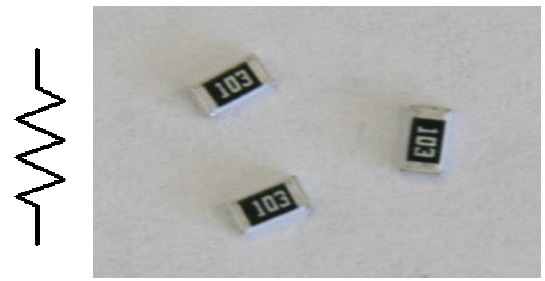
Variable Resistors

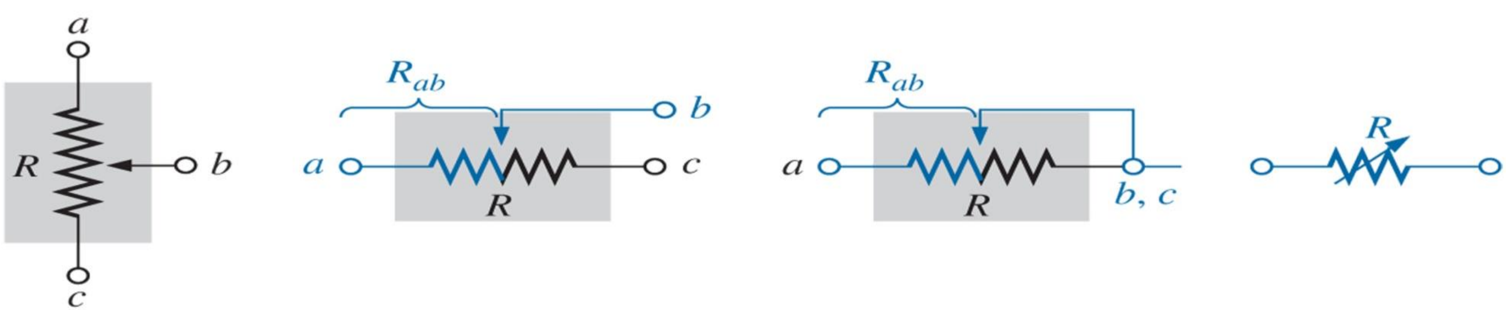


Carbon Film



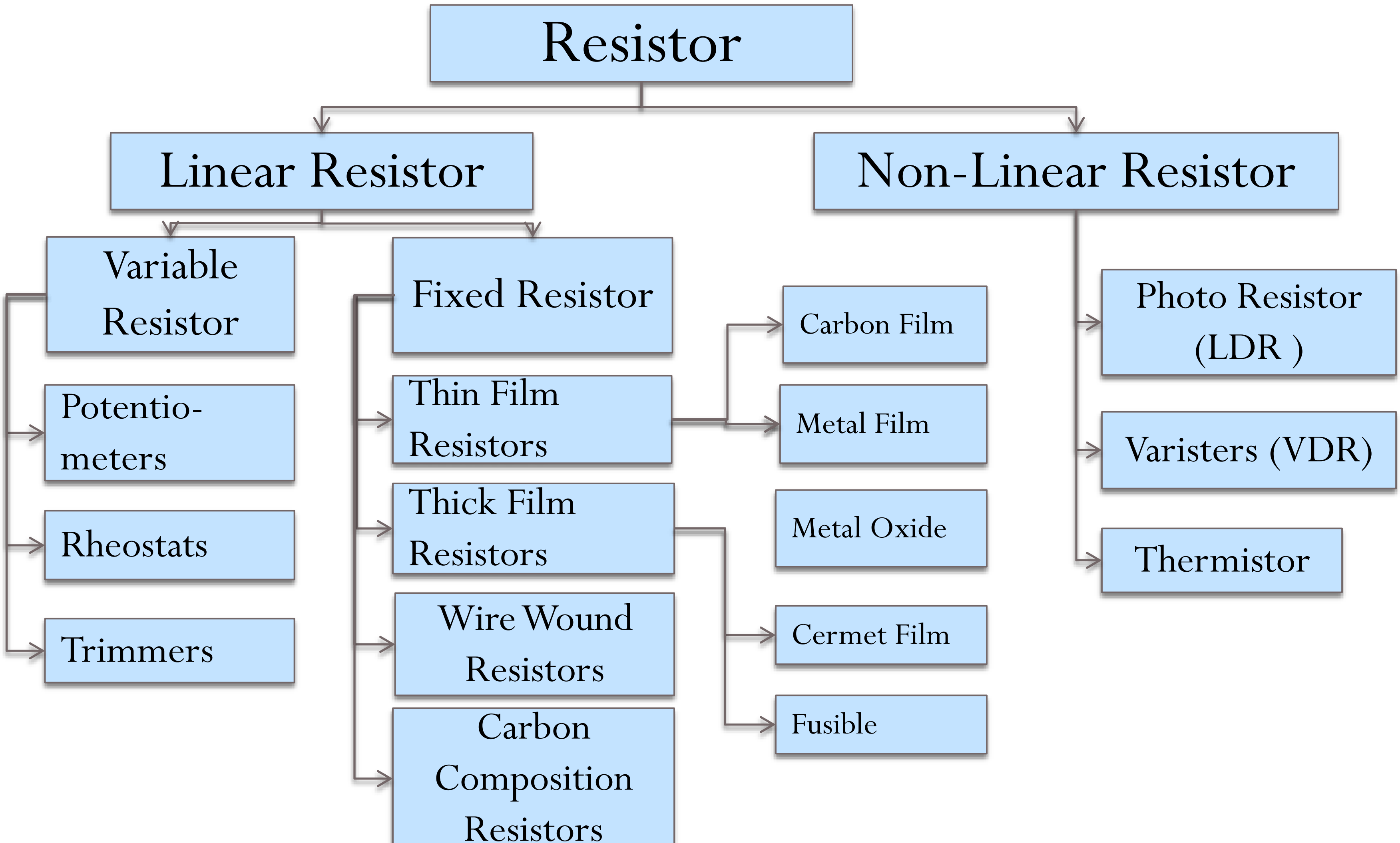
Surface Mount Resistors





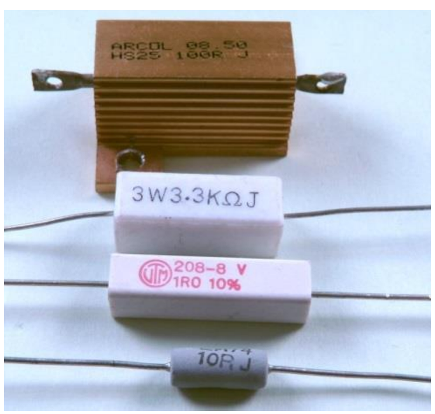
(a) (b) (c) (d)

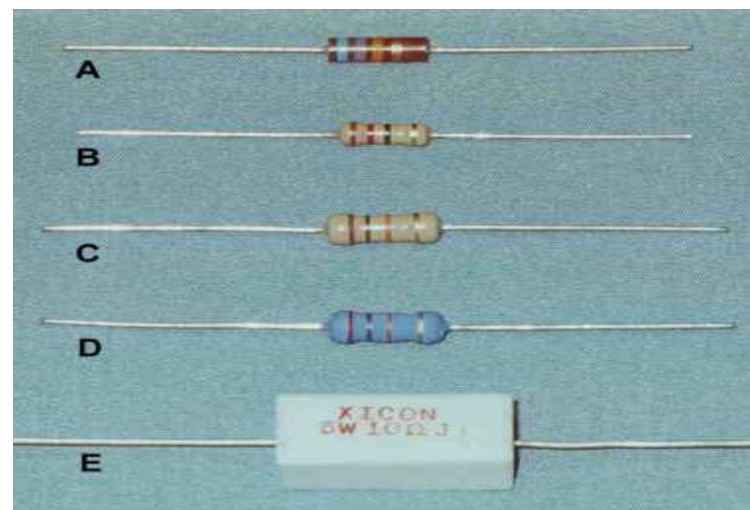
Resistors: Types and Package Styles



Fixed and Variable Resistors

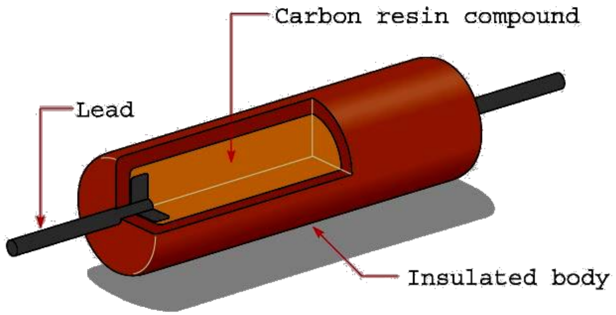
- A **fixed resistor** is, as the name suggests, a fixed predetermined value. Lower power resistors are either made from carbon film or metal film. Power resistors can be either ceramic or wire wound.
- Fixed resistors have only one Ohmic value, which cannot be changed or adjusted.
- Fixed resistors come in a variety of different shapes, sizes and forms
- Fixed resistors are made of
  - Carbon composition
  - Metal films
  - High-resistance wire



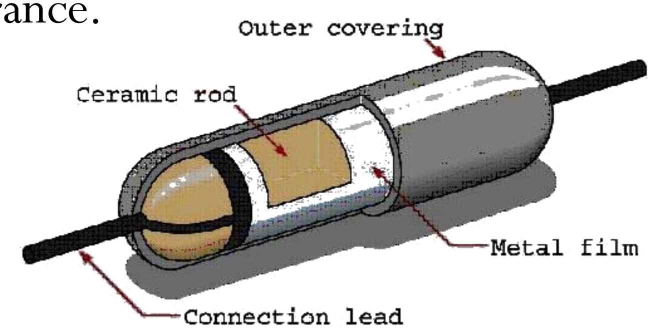


Fix type Resistor

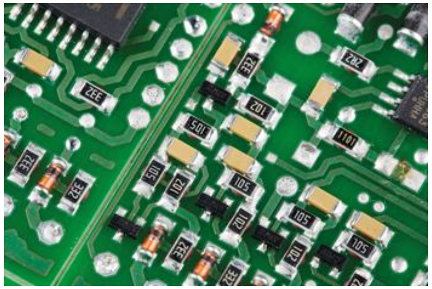
- One type of fixed resistor is the composition carbon resistor.

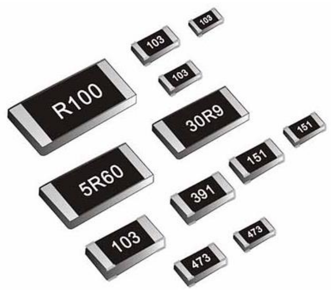


- **Metal film** resistors are another type of fixed resistor. These resistors are superior to carbon resistors because their ohmic value does not change with age and they have improved tolerance.

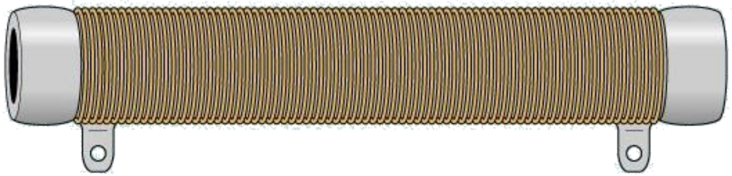


- **SMD Resistors:** Surface Mount Resistors or SMD Resistors





- **Wire-wound** resistors are fixed resistors that are made by winding a piece of resistive wire around a ceramic core. These are used when a high-power rating is required.



Variable Resistors

- A **variable resistor** is, as the name suggests, able to have a range of resistances between **zero** and some stated **maximum** resistance.
- Therefore, a $10\,\text{k}\Omega$ variable resistor can have any value between $0\,\Omega$ and $10\,\text{k}\Omega$ as determined by the user.
- Variable resistors are used to **control the current** in a circuit, an example might be dimming a bulb or slowing a motor.

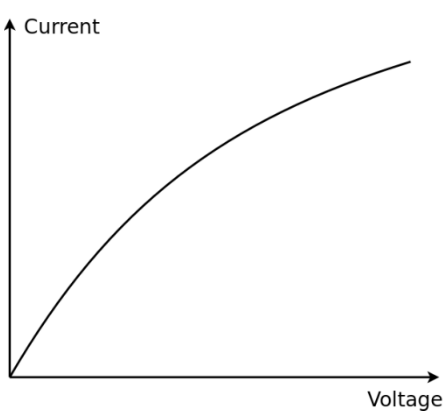


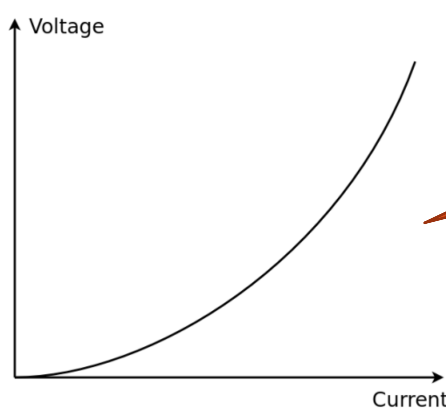
- Variable resistors can have two or three terminals.
- Variable resistors are classified as a *rheostat* or a *potentiometer*.
    - Rheostat: Two- terminal device
    - Potentiometer: Three-terminal device


Wire, Heater, Filament

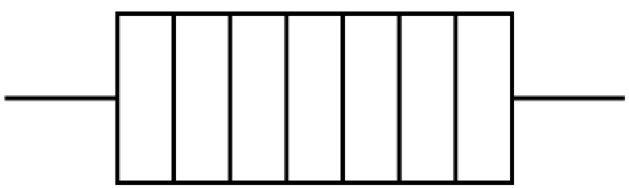
Resistance wire is a material such as constantan or nichrome, that has a high resistance compared to normal conductors such as copper and aluminium.

Because a length of resistance wire has significant resistance, it will dissipate energy – i.e. it will get hot – this is useful for heating elements in devices such as toasters.





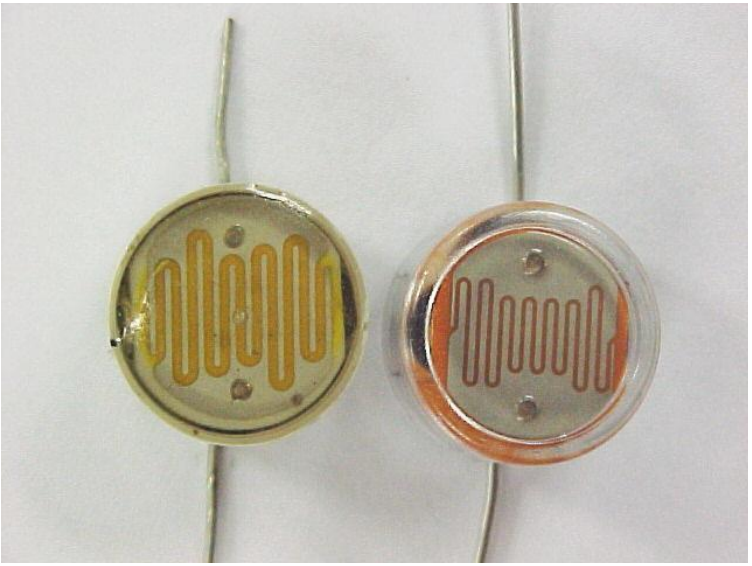
The **Resistance** of a wire **increases** as it gets **hot**

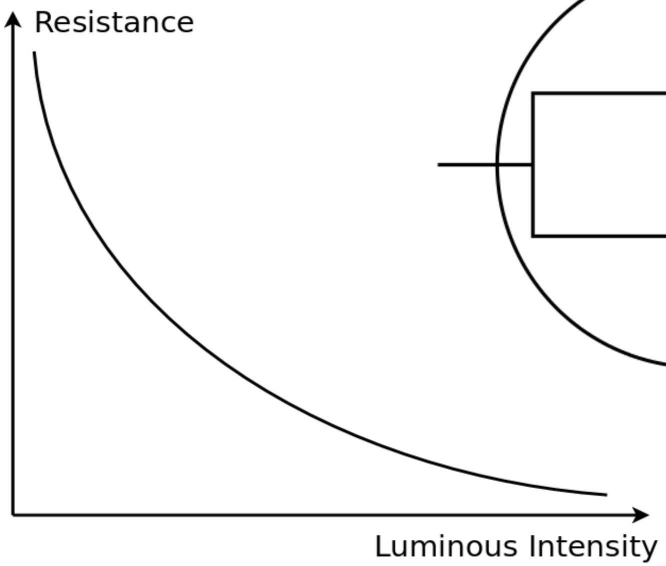


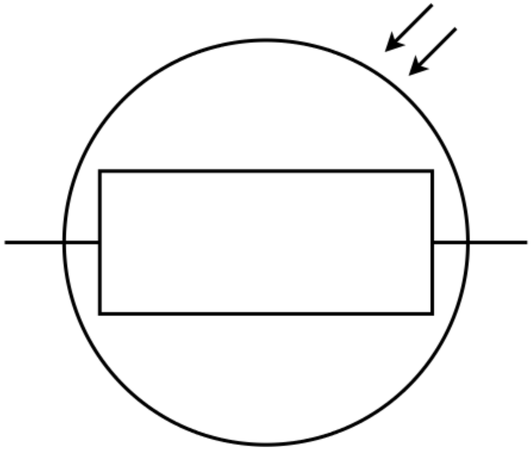
Light Dependent Resistor

A Light Dependent Resistor (LDR) is a semiconductor device.

The resistance of the semiconductor reduces when energy is supplied. Therefore, the design of an LDR is such that the resistance of the LDR reduces as the light level increases.

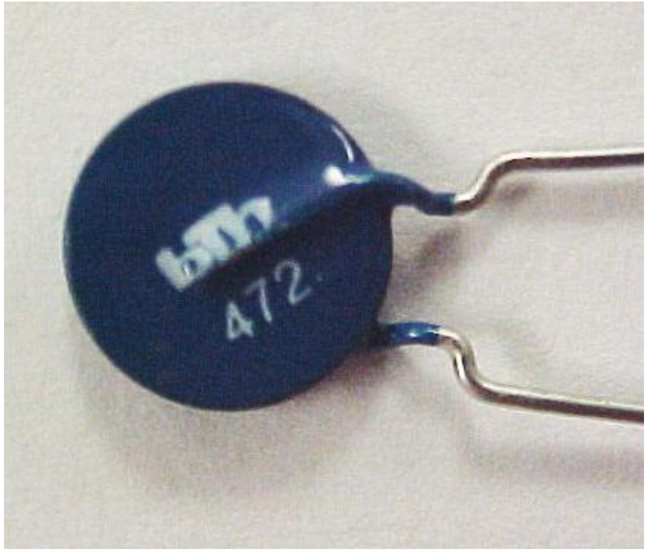


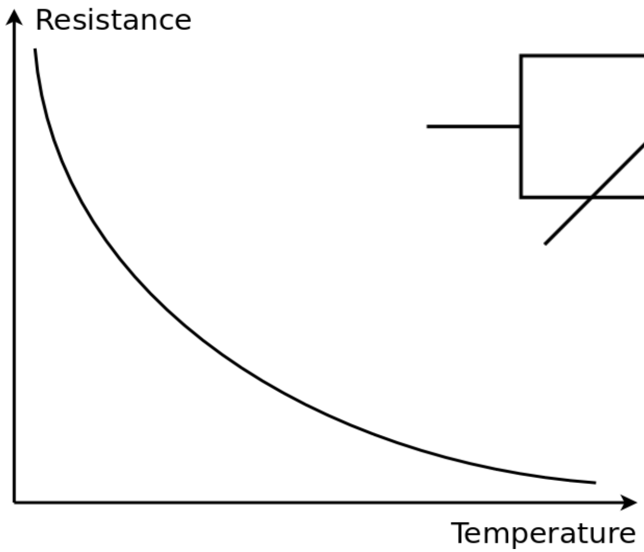


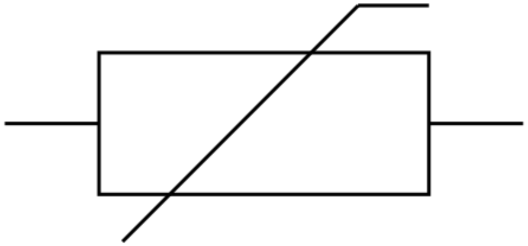


NTC Thermistor

An NTC thermistor, is another semiconductor device. The resistance of the semiconductor reduces when thermal energy is supplied. Therefore, the resistance of the thermistor reduces as the temperature increases. This is the "usual" type of thermistor used in electronics. NTC means Negative Temperature Coefficient.



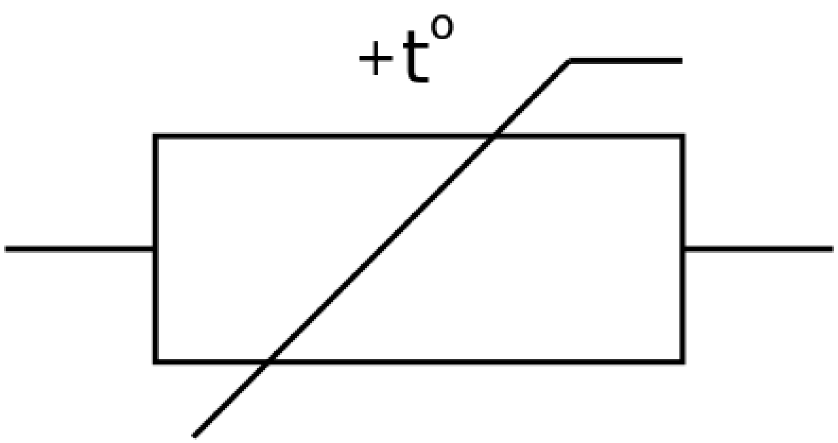




PTC Thermistor

A PTC thermistor behaves in the opposite manner to a regular NTC thermistor. In the case of a PTC thermistor, the resistance of the thermistor increases as the temperature increases. These are the more unusual type of thermistor.

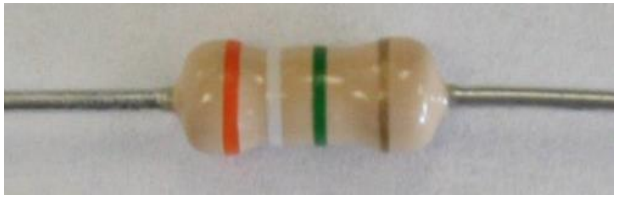
PTC means Positive Temperature Coefficient



The Resistance-Temperature graph for a PTC Thermistor is more complex than for an NTC Thermistor. The resistance rises sharply at a certain threshold temperature.

Determining a Resistor's Value

- Color Code
- Resistors are labeled with color bands that specify the resistor's nominal value.
- The nominal value is the resistor's face value.



- Measured Value
- A digital multimeter can measure the resistor's actual resistance value.

- Find a 1,000Ω resistor in your kit.
- Measure its actual resistance.

color	digit
black	0
brown	1
red	2
orange	3
yellow	4
green	5
blue	6
violet	7
gray	8
white	9

Resistor Color Code

- Manufacturers typically use a color band system known as the resistor color code.

- The **resistor color code** can be used to determine the resistor's ohmic value and tolerance.

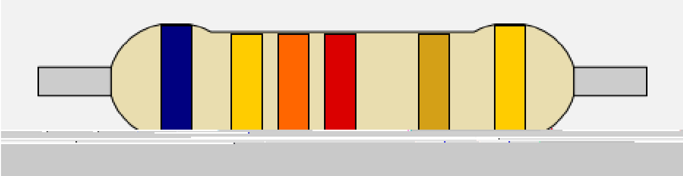
- The power rating is *not* indicated in the resistor color code and must be determined by experience using the physical size of the resistor as a guide.

4 band Resistor

- For resistors with ±5% or ±10% tolerance, the color code consists of 4 color bands.

5 band Resistor

- For resistors with ±1% or ±2% tolerance, the color code consists of 5 or 6 bands.



6 band Resistor

Resistor Color Coding: Tolerance

- The tolerance of a resistor is the deviation that a resistor may vary from its nominal value resistance, measured at a fixed temperature with no load applied.
  - The resistor tolerance is the amount by which the resistance of a resistor may vary from its stated value.
  - The larger the resistor tolerance, the more it may vary, either up or down, from its nominal value.
  - The smaller the resistor tolerance, the less it varies from its nominal value and, thus, the more stable it is.

- The most common way of specifying resistor tolerance is by percentage. When specified by percentage value, this percentage means the amount by which a resistor may vary from its nominal value. For example, a resistor which has a tolerance of 10% may vary 10% from its nominal value.

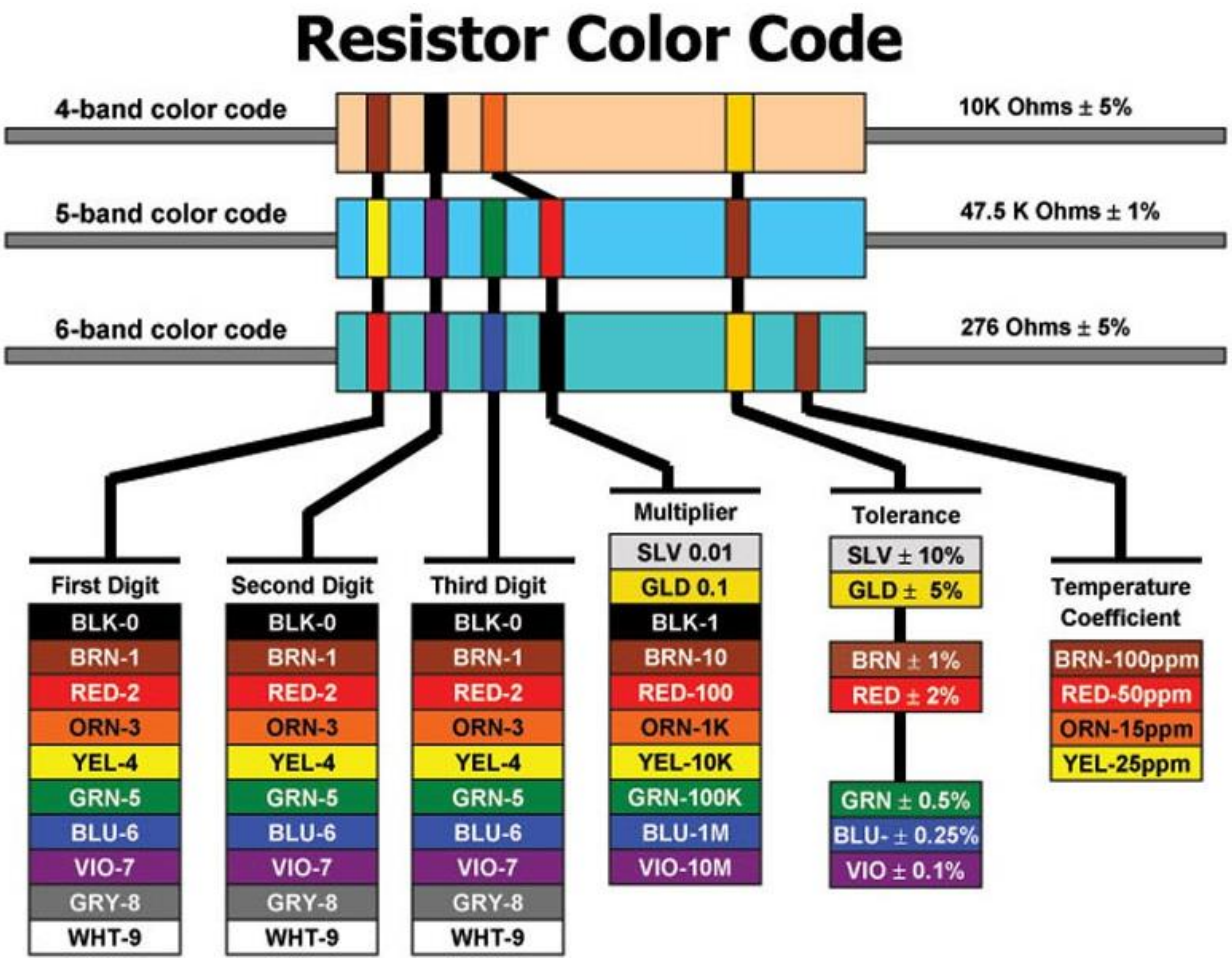
- Just to see some practical examples of what tolerance is, consider a 500Ω resistor with a 10 percent tolerance. This means that the resistance of it can be anywhere from as low as 450Ω to as high as 550Ω. On the other hand, if the same 500Ω resistor has a 1 percent tolerance, its resistance can be between 495Ω and 505Ω. Lower percent tolerances equal more precision (less variance) in resistance values.

Resistor Color Coding: Tolerance

- The temperature coefficient is to the right of the tolerance band and usually positioned on the cap as a wide band.
- When in total 5 or 6 bands are used, the last band will always be the wider one.
- The resistance code includes first two or three significant figures of the resistance value (in ohms) followed by multiplier. This is the factor by which the significant figure value must be multiplied to find the resistance value.
- Whether two or three significant figures are represented depends on tolerance in the value. For 2% and higher tolerance, requires two bands and for 1% and lower tolerance requires three bands.

Resistor Color Coding:

An international and universally accepted resistor color code scheme was developed many years ago as a simple and quick way of identifying a resistors ohmic value no matter what its size or condition. It consists of a set of individual-coloured rings or bands in spectral order representing each digit of the resistors value.

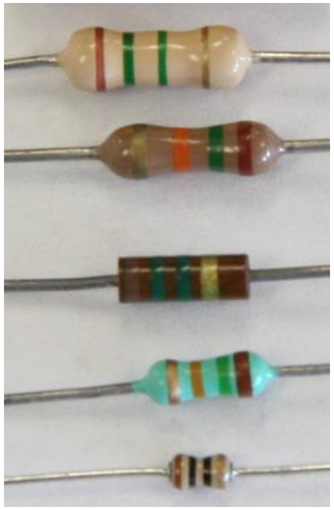


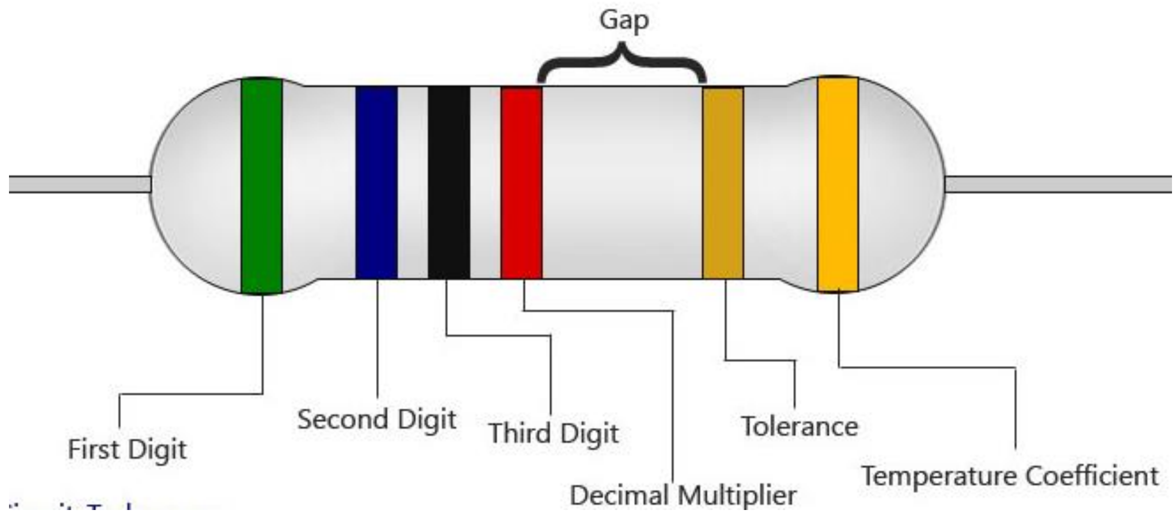
Color Code of Resistor

	Color	Digit	Multiplier	Tolerance
Resistance value, first three bands: First band–1st digit Second band– 2nd digit *Third band– multiplier (number of zeros following the 2nd digit)	Black	0	10^0	
	Brown	1	10^1	1% (five band)
	Red	2	10^2	2% (five band)
	Orange	3	10^3	
	Yellow	4	10^4	
	Green	5	10^5	
	Blue	6	10^6	
	Violet	7	10^7	
	Gray	8	10^8	
	White	9	10^9	
Fourth band– tolerance	Gold	±5%	10^{-1}	5% (four band)
	Silver	±10%	10^{-2}	10% (four band)
	No band	±20%		

* For resistance values less than 10Ω, the third band is either gold or silver. Gold is for a multiplier of 0.1 and silver is fo a multiplier of 0.01.

How to hold Resistor

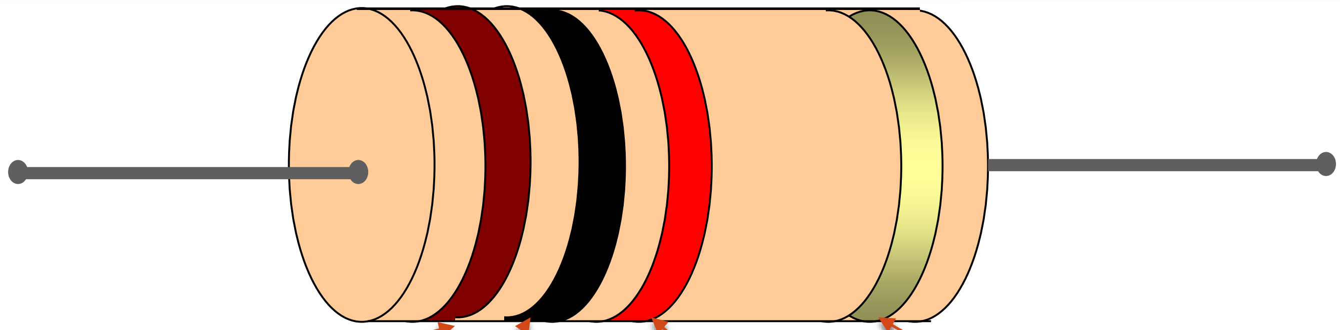




1. Many resistors have some of the color bands grouped closer together or grouped toward one end. Hold the resistor with these grouped bands to your left. Always read resistors from left to right.

2. Resistors never start with a metallic band on the left. If you have a resistor with a gold or silver band on one end, you have a 5% or 10% tolerance resistor. Position the resistor with this band on the right side and again read your resistor from left to right.

4-Band Resistors



1^{st} Band = 1^{st} Significant Digit

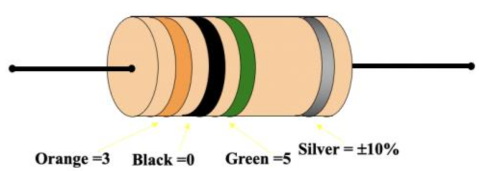
2^{nd} Band = 2^{nd} Significant Digit

3^{rd} Band = Multiplier

4^{th} Band = Tolerance

$$\underline{\quad}\ \ \underline{\quad} \times 10^{\underline{\quad}}\ \Omega \pm \underline{\quad}\ \%$$

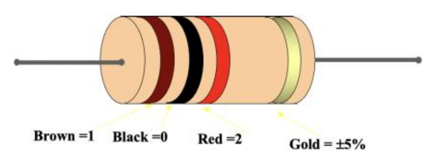
Examples:



$$\underline{3}\ \ \underline{0} \times 10^{\underline{5}}\ \Omega \pm \underline{10}\ \%$$

Resistor nominal value $= 30\times10^5\Omega$
$= 3{,}000{,}000\Omega$
$= 3M\Omega$.

Tolerance = ±10%



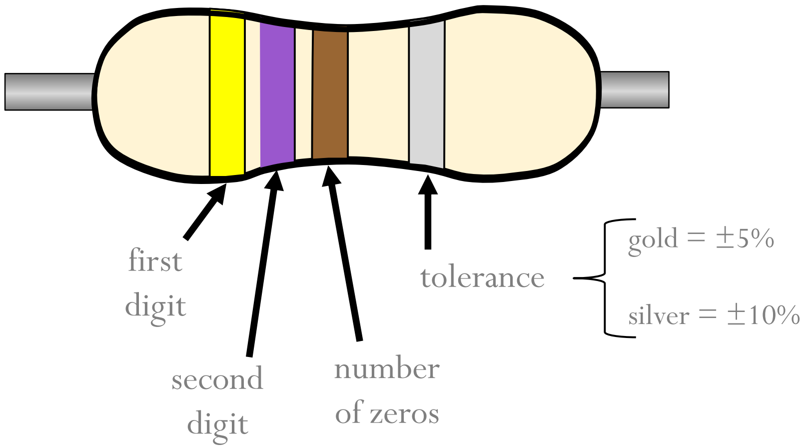
$$\underline{1}\ \ \underline{0} \times 10^{\underline{2}}\ \Omega \pm \underline{5}\ \%$$

Nominal value $= 10\times10^2\Omega$
$= 1{,}000\Omega$

Tolerance = ±5%.

Using the Color Code to Determine Resistance

color	digit
black	0
brown	1
red	2
orange	3
yellow	4
green	5
blue	6
violet	7
gray	8
white	9



- What is the value of the resistor above?

  Yellow = 4

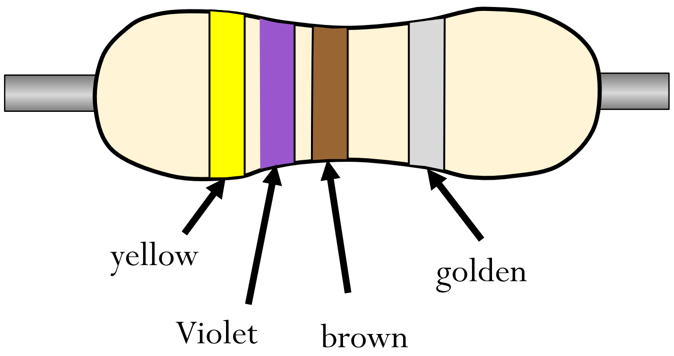
  Violet = 7

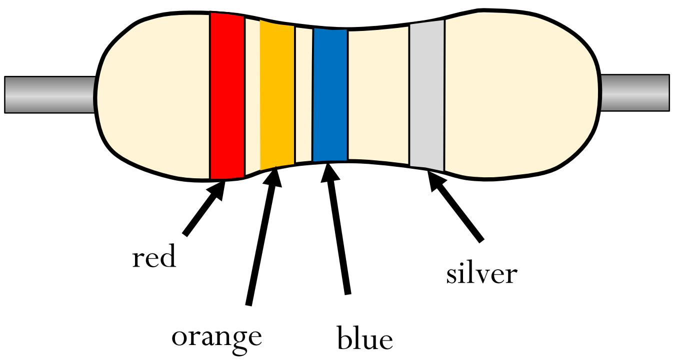
  Brown = Add 1 Zero to value

Resistance = 470Ω

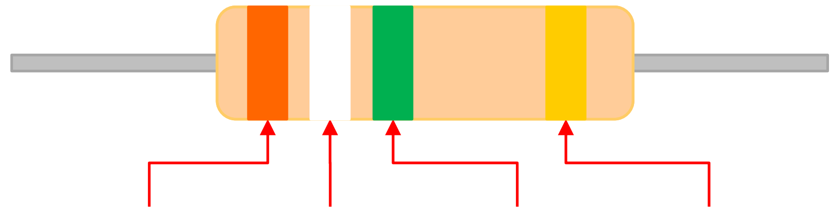
Task:

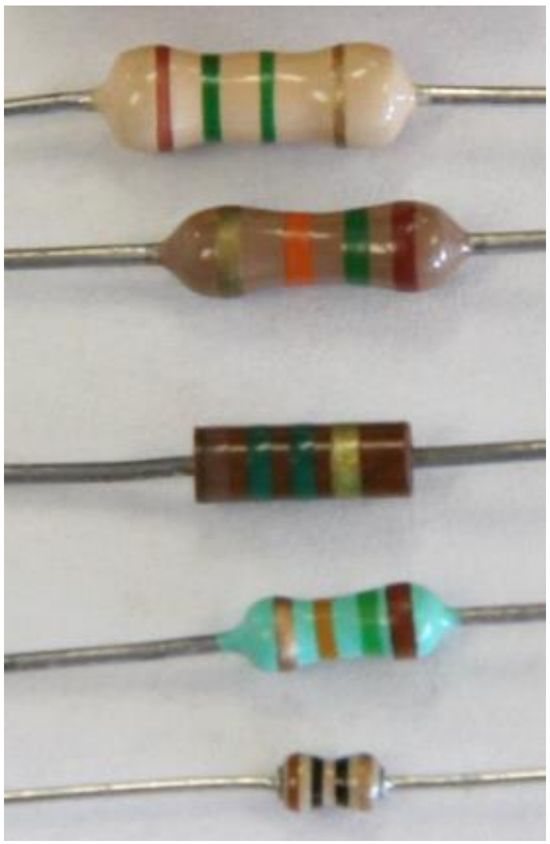
color	digit
black	0
brown	1
red	2
orange	3
yellow	4
green	5
blue	6
violet	7
gray	8
white	9





Resistor Color Code



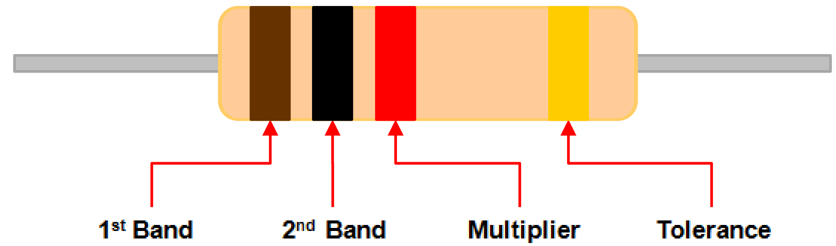


	1st Band	2nd Band	Multiplier	Tolerance
NONE				20%
Silver			0.01	10%
Gold			0.1	5%
Black	0	0	1	
Brown	1	1	10	
Red	2	2	100	
Orange	3	3	1K	
Yellow	4	4	10K	
Green	5	5	100K	
Blue	6	6	1M	
Violet	7	7	10M	
Gray	8	8	100M	
White	9	9	1000M	

Resistor Value: Example

Example:

Determine the nominal value for the resistor shown.

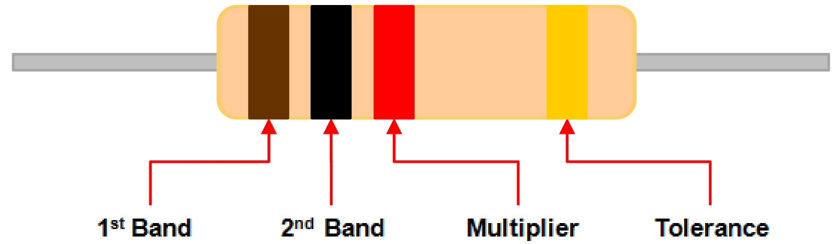


NONE				20%
Silver			0.01	10%
Gold			0.1	5%
Black	0	0	1	
Brown	1	1	10	
Red	2	2	100	
Orange	3	3	1K	
Yellow	4	4	10K	
Green	5	5	100K	
Blue	6	6	1M	
Violet	7	7	10M	
Gray	8	8	100M	
White	9	9	1000M	

Resistor Value: Example

Example:

Determine the nominal value for the resistor shown.



	1st Band	2nd Band	Multiplier	Tolerance
NONE				20%
Silver			0.01	10%
Gold			0.1	5%
Black	0	0	1	
Brown	1	1	10	
Red	2	2	100	
Orange	3	3	1K	
Yellow	4	4	10K	
Green	5	5	100K	
Blue	6	6	1M	
Violet	7	7	10M	
Gray	8	8	100M	
White	9	9	1000M	

Solution:

$10 \times 100\ \Omega\ \pm 5\%$

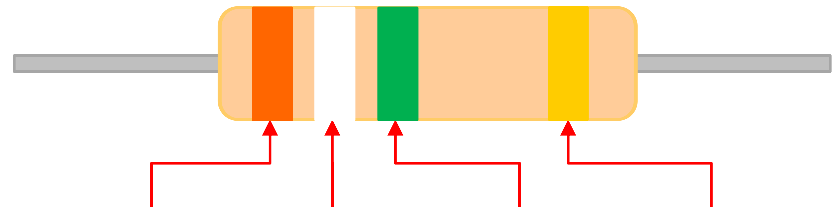
$1000\ \Omega\ \pm 5\%$

$1\ \mathrm{K}\ \Omega\ \pm 5\%$

Resistor Value: Example

Example:

Determine the nominal value for the resistor shown.

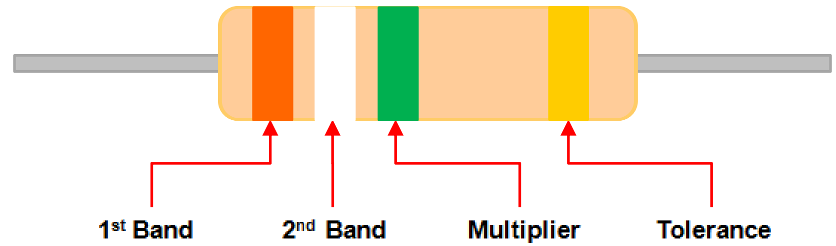


	1^{st} Band	2^{nd} Band	Multiplier	Tolerance
NONE				20%
Silver			0.01	10%
Gold			0.1	5%
Black	0	0	1	
Brown	1	1	10	
Red	2	2	100	
Orange	3	3	1K	
Yellow	4	4	10K	
Green	5	5	100K	
Blue	6	6	1M	
Violet	7	7	10M	
Gray	8	8	100M	
White	9	9	1000M	

Resistor Value: Example

Example:

Determine the nominal value for the resistor shown.



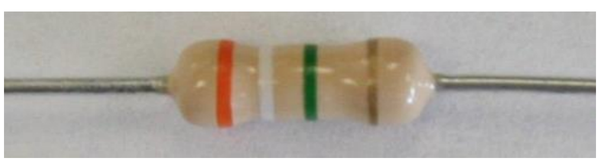
	1st Band	2nd Band	Multiplier	Tolerance
NONE				20%
Silver			0.01	10%
Gold			0.1	5%
Black	0	0	1	
Brown	1	1	10	
Red	2	2	100	
Orange	3	3	1K	
Yellow	4	4	10K	
Green	5	5	100K	
Blue	6	6	1M	
Violet	7	7	10M	
Gray	8	8	100M	
White	9	9	1000M	

Solution:

$39 \times 100K\ \Omega\ \pm 5\%$

$3900000\ \Omega\ \pm 5\%$

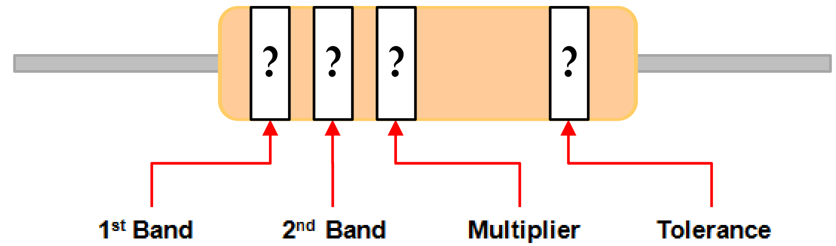
$3.9\ M\Omega\ \pm 5\%$



Resistor Value: Example

Example:

Determine the color bands for a $1.5\ K\Omega\ \pm 5\%$ resistor.



	1st Band	2nd Band	Multiplier	Tolerance
NONE				20%
Silver			0.01	10%
Gold			0.1	5%
Black	0	0	1	
Brown	1	1	10	
Red	2	2	100	
Orange	3	3	1K	
Yellow	4	4	10K	
Green	5	5	100K	
Blue	6	6	1M	
Violet	7	7	10M	
Gray	8	8	100M	
White	9	9	1000M	

Resistor Value: Example

Example:

Determine the color bands for a 1.5 K Ω ±5% resistor.

Solution:

1.5 K Ω ±5%

1500 Ω ±5%

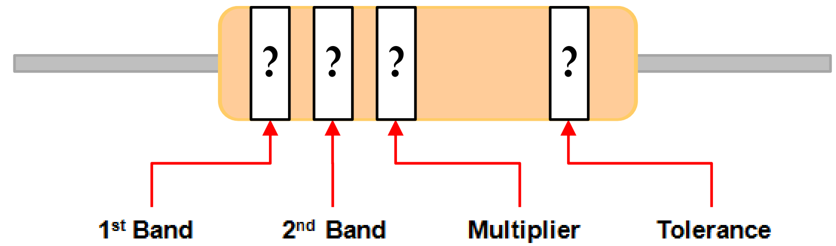
15 x 100 Ω ±5%

1: Brown

5: Green

100: Red

5%: Gold

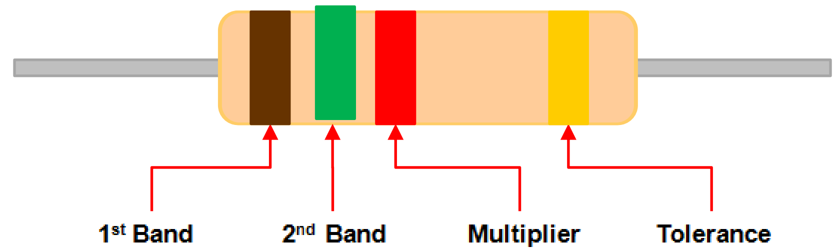


	1st Band	2nd Band	Multiplier	Tolerance
NONE				20%
Silver			0.01	10%
Gold			0.1	5%
Black	0	0	1	
Brown	1	1	10	
Red	2	2	100	
Orange	3	3	1K	
Yellow	4	4	10K	
Green	5	5	100K	
Blue	6	6	1M	
Violet	7	7	10M	
Gray	8	8	100M	
White	9	9	1000M	

Resistor Value: Example

Example:

Determine the color bands for a 1.5 K Ω ±5% resistor.



	1st Band	2nd Band	Multiplier	Tolerance
NONE				20%
Silver			0.01	10%
Gold			0.1	5%
Black	0	0	1	
Brown	1	1	10	
Red	2	2	100	
Orange	3	3	1K	
Yellow	4	4	10K	
Green	5	5	100K	
Blue	6	6	1M	
Violet	7	7	10M	
Gray	8	8	100M	
White	9	9	1000M	

Solution:

1.5 K Ω ±5%

1500 Ω ±5%

15 x 100 Ω ±5%

1: Brown

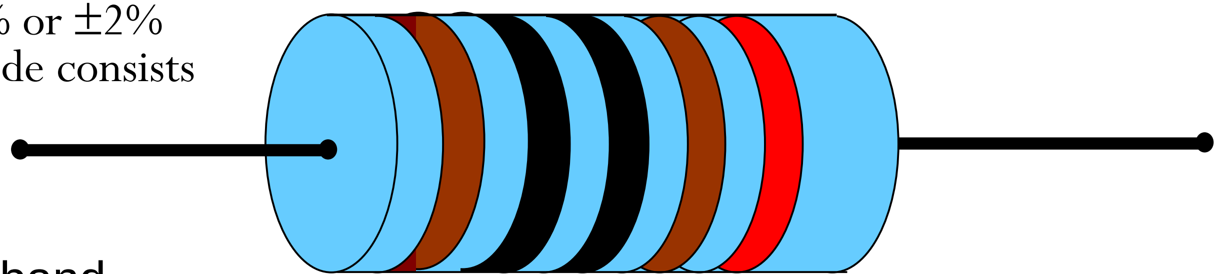
5: Green

100: Red

5%: Gold

5-Band Resistors

- For resistors with ±1% or ±2% tolerance, the color code consists of 5 bands.



- The template for 5-band resistors is:

1st Band = 1st Significant Digit

2nd Band = 2nd Significant Digit

3rd Band = 3rd Significant Digit

4th Band = Multiplier

5th Band = Tolerance

$$\_\_\_\ \ \_\_\_\ \ \_\_\_ \times 10^{\_\_\_}\ \Omega \pm \_\_\_\ \%$$

Brown = 1 **Black =0** **Black = 0** **Brown = 1** **Red = ± 2%**

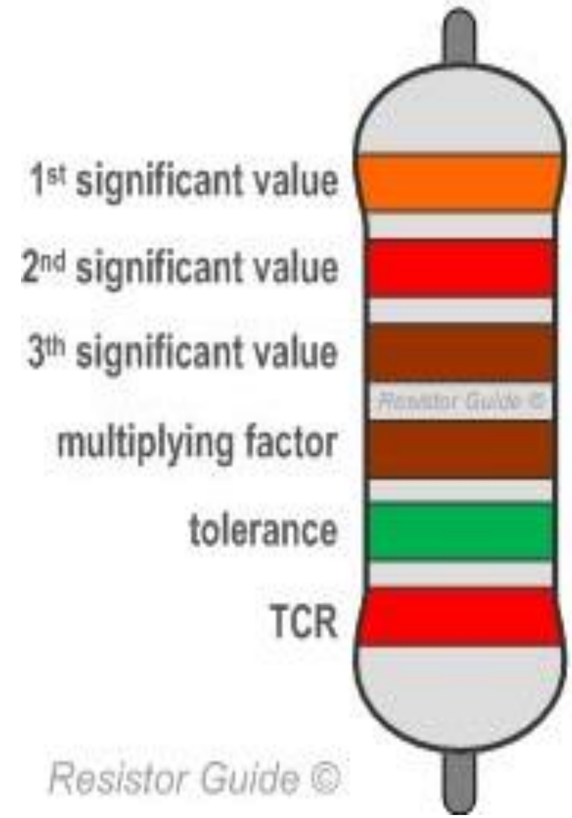
$$\underline{1}\ \ \underline{0}\ \ \underline{0} \times 10^{\underline{1}}\ \Omega \pm \underline{2}\ \%$$

Resistor nominal value = $100\times10^{1}\Omega = 1{,}000\Omega = 1\text{k}\Omega$.

Tolerance = ±2%

6-Band Resistors

- The template for 6-band resistors is:



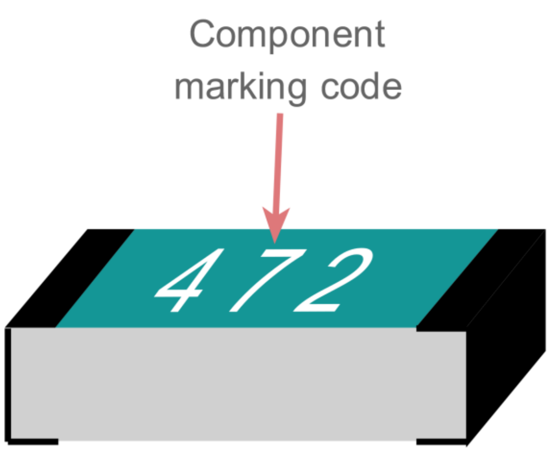
- Resistors with 6 bands are usually for high precision resistors that have an additional band to specify the temperature coefficient (ppm/K).
- The most common color for the sixth band is brown (100 ppm/K).
- This means that for a temperature change of 10 ˚C, the resistance value can change 0.1%.

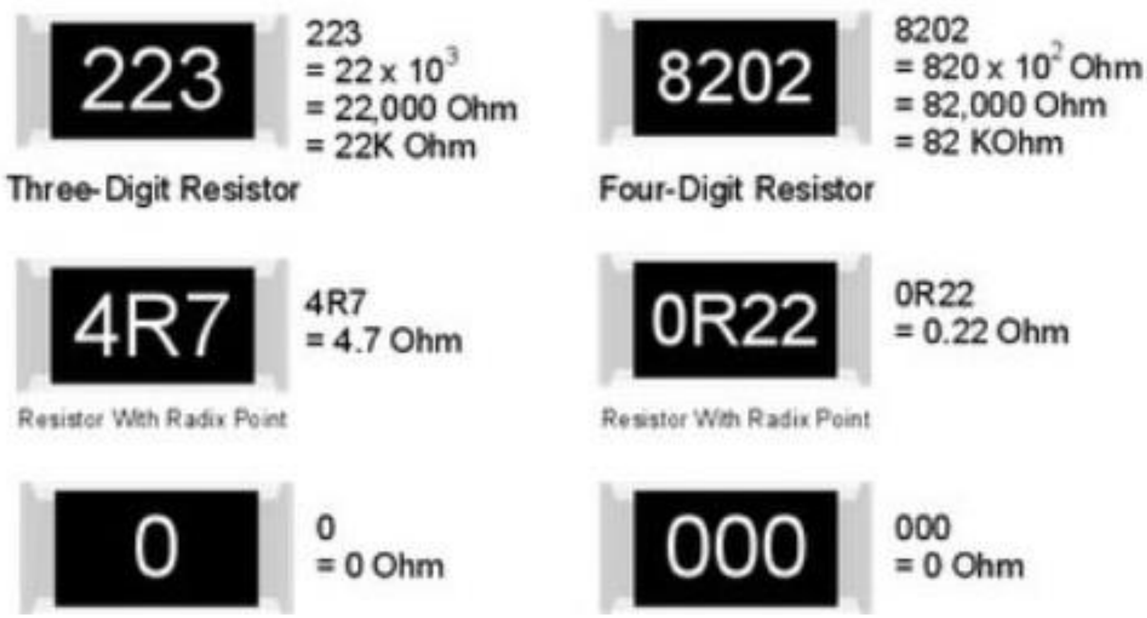
Orange (3) .
Red (2). .
Brown (1). .
Brown (x10)
Green (0.5%).
Red(50 ppm/K)
3.21 k Ω 0.5% 50 ppm/K.

$\underline{3}\ \underline{2}\ \underline{1} \times 10^{\underline{1}}\ \Omega \pm \underline{0.5}\ \%\ \underline{50}$ ppm/K

SMD Resistor Coding

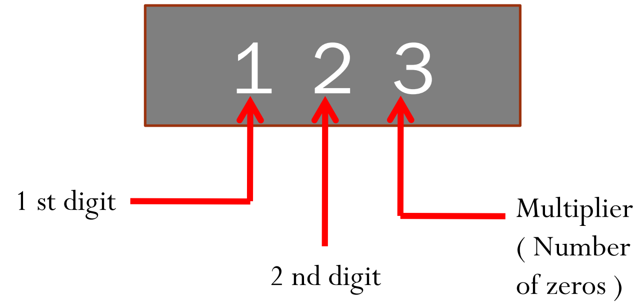
- The first two (or 3) digits are the first two (or 3) digits of the resistance in ohms, and the third(or 4th) is the number of zeros to follow - the 'multiplier'.
- Resistances of less than 10 ohms have a 'R' to indicate the position of the decimal point.





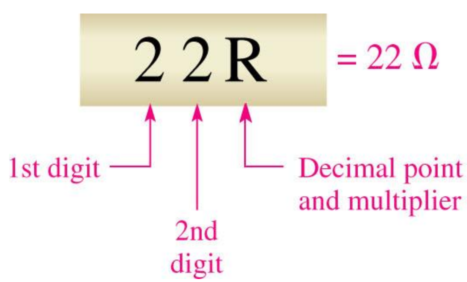
Alphanumeric Labeling

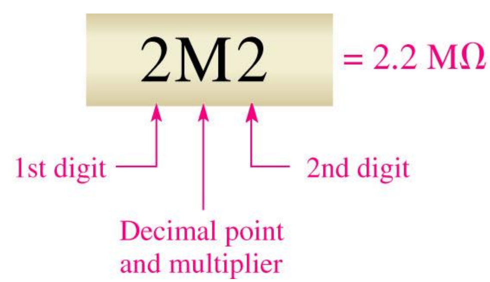
- Consist of either all numbers (numeric) or a combination of number and letters (alphanumeric)
- Numeric Labeling uses of 3 digits to indicate their resistance value.

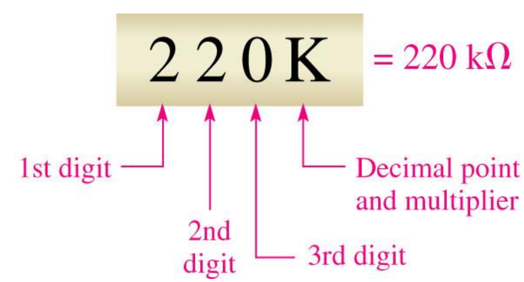


= 12,000 Ω = 12 kΩ

- Two or three digits, and one of the letters R, K, or M are used to identify a resistance value.
- The letter is used to indicate the multiplier, and its position is used to indicate decimal point position.







SMD Resistor Coding: EIA SMD Resistor Code Scheme

EIA SMD RESISTOR CODE SCHEME MULTIPLIERS

CODE	SIG FIGS	CODE	SIG FIGS	CODE	SIG FIGS	CODE	SIG FIGS
01	100	25	178	49	316	73	562
02	102	26	182	50	324	74	576
03	105	27	187	51	332	75	590
04	107	28	191	52	340	76	604
05	110	29	196	53	348	77	619
06	113	30	200	54	357	78	634
07	115	31	205	55	365	79	649
08	118	32	210	56	374	80	665
09	121	33	215	57	383	81	681
10	124	34	221	58	392	82	698
11	127	35	226	59	402	83	715
12	130	36	232	60	412	84	732
13	133	37	237	61	422	85	750
14	137	38	243	62	432	86	768
15	140	39	249	63	442	87	787
16	143	40	255	64	453	88	806
17	147	41	261	65	464	89	825
18	150	42	267	66	475	90	845
19	154	43	274	67	487	91	866
20	158	44	280	68	499	92	887
21	162	45	287	69	511	93	909
22	165	46	294	70	523	94	931
23	169	47	301	71	536	95	953
24	174	48	309	72	549	96	976

EIA SMD RESISTOR CODE SCHEME

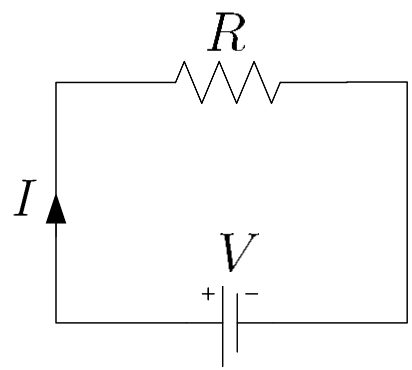
CODE	MULTIPLIER
Z	0.001
Y or R	0.01
X or S	0.1
A	1
B or H	10
C	100
D	1 000
E	10 000
F	100 000

For example, a resistor that is marked 68X can be split into two elements. 68 refers to the significant figures 499, and X refers to a multiplier of 0.1.

Therefore, the value indicated is 499 x 0.1 = 49.9Ω.

Analysis Of Resistors In Circuit

Voltage, Current and Resistance

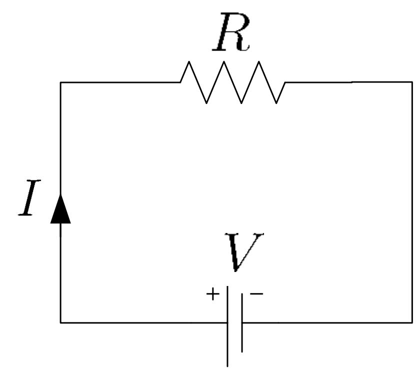


- **Current**
  - describes the flow of positive charges through the circuit
  - measured in units of **Amperes (A)**
  - is, by theory, defined as

$$I = \frac{dQ}{dt}$$

where I is the current, and Q is the charge, in Coulombs (C).

Voltage, Current and Resistance

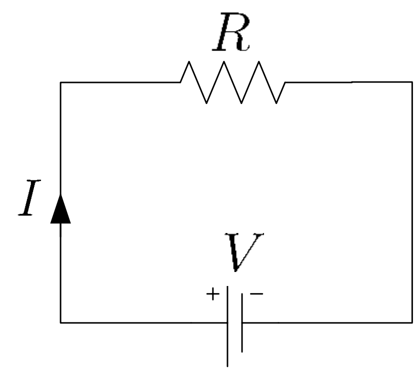


- **Voltage**
  - describes the potential for current to flow in the circuit
  - measured in units of **Volts (V)**
  - Voltage is related to energy, measured in **Joules**.
  - The energy required to move a particle with **Q** Coulombs from a place of **0** V to a place with **V** V is

$$E = Q \cdot V$$

where E represents the energy (in Joules).

Voltage, Current and Resistance



- **Resistor**
  - is a device that resists the flow of current
  - allows current to flow, but the amount depends on the value of the resistor and the voltage applied
  - The value of the resistor, or simply resistance, is measured in units of **Ohms (Ω)**
  - By Ohm's law, we have

$$V = I \cdot R$$

where R represents the resistance (in Ω).

Ohm's Law

- The ratio of the potential difference applied across a conductor and current flowing through it remains constant provided physical state i.e, temperature etc of the conductor remains constant

- V/I = Constant = R where R is known as the resistance of the conductor

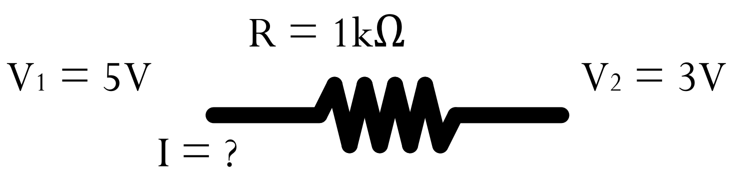
- Ohm's law cannot be applicable for circuits consists of electronic valves or thyristors, diodes etc because these elements are not bilateral – i.e, they behave in different way, when the direction of flow of current is reversed as in the case of a diode.

- Ohm's law cannot be applied to the circuits consisting of non-linear elements such as thyrite, electric arc etc.

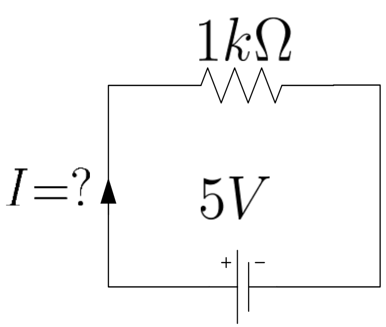
Ohm's Law

- Description
  - Relates the difference in potential (voltage) of a circuit as a function of the current and the resistance of the circuit
- Formula
  - V = I·R

Example



$(V_1 – V_2) = I·R$
$(5V – 3V) = I·(1000Ω)$
$I = 2V/1000Ω = 0.002A$

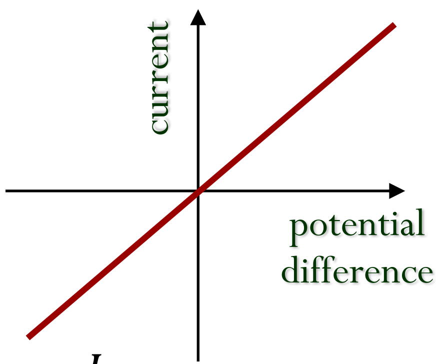


$$5 = I \cdot 1000$$
$$\implies I = 5/1000 = 5mA$$

Current vs potential difference

How does the current vary with potential difference for some typical devices?

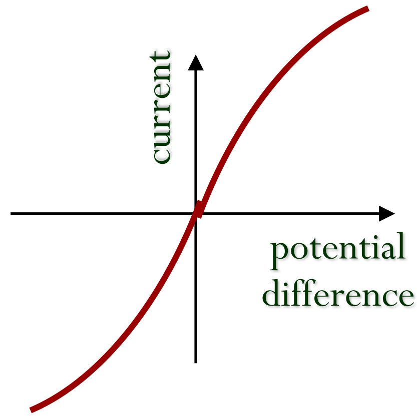
metal at const. temp.



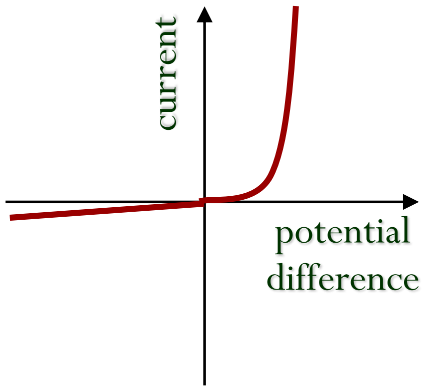
$$as\ \frac{I}{V}\ is\ constant,$$

$$so\ is\ R = \frac{V}{I}$$

filament lamp



diode

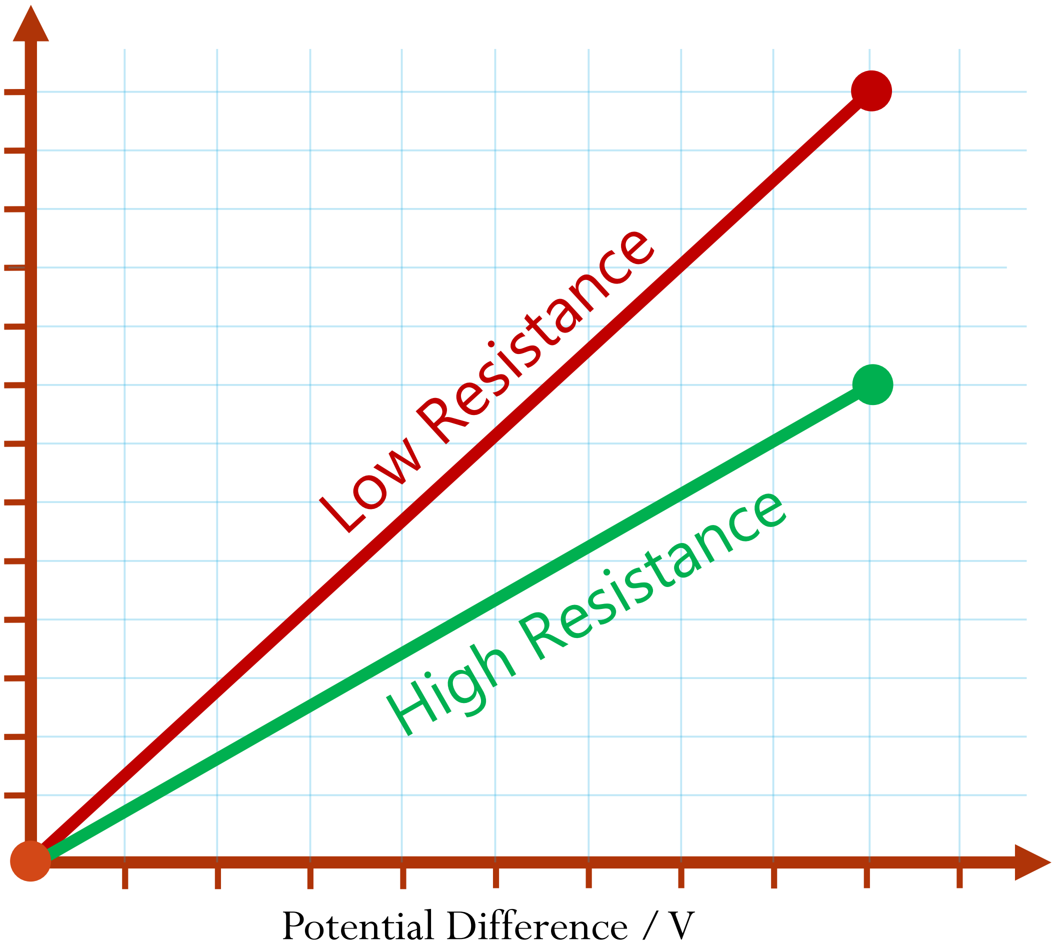


devices are non-ohmic if resistance changes

Devices for which current through them is directly proportional to the potential difference across device are said to be ‘ohmic devices’ or ‘ohmic conductors’ or simply **resistors**. In other words the resistance stays constant as the voltage changes.

There are very few devices that are trully ohmic. However, many useful devices obey the law at least over a reasonable range.

Graphing Ohm's Law

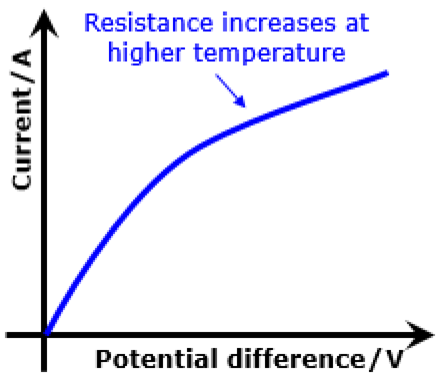


Linear Relationship means that our component is Ohmic.

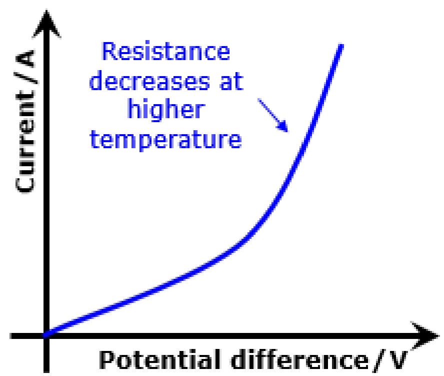
Resistance is constant

Graphing Ohm's Law

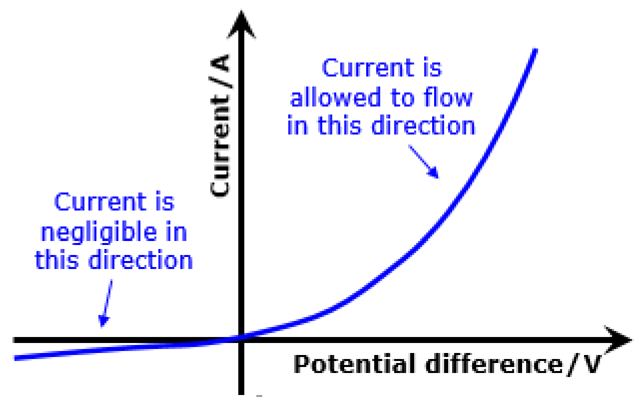
Many/most electrical resistors don't follow Ohm's Law all of the time... For example, incandescent light bulbs have much more resistance as they heat up



***I-V* Graph For A Filament Lamp**



***I-V* Graph For A Thermistor**



***I-V* Graph For A Semiconductor Diode**

Non-linear Relationship means that our component is Non-ohmic

Voltage, Current and Resistance

- **Power**
  - is the rate of energy dissipation with respect to time
  - is in units of Joules per second, or **Watts (W)**
  - is given by

$$P = \frac{dE}{dt} = I \cdot V$$

where P represents the power (in W).

- By Ohm's law, we have

$$P = V^2/R = I^2 R$$

Electrical Power in Circuits

- Electrical Power, (P) in a circuit is the rate at which energy is absorbed or produced within a circuit. A source of energy such as a voltage will produce or deliver power while the connected load absorbs it.

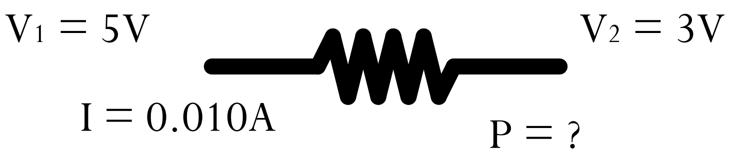
- Light bulbs and heaters for example, absorb electrical power and convert it into either heat, or light, or both. The higher their value or rating in watts the more electrical power they are likely to consume.

- The quantity symbol for power is P and is the product of voltage multiplied by the current with the unit of measurement being the Watt (W). Prefixes are used to denote the various multiples or sub-multiples of a watt, such as: milliwatts (mW) or kilowatts (kW).

- Then by using Ohm's law and substituting for the values of V, I and R the formula for electrical power can be found as:

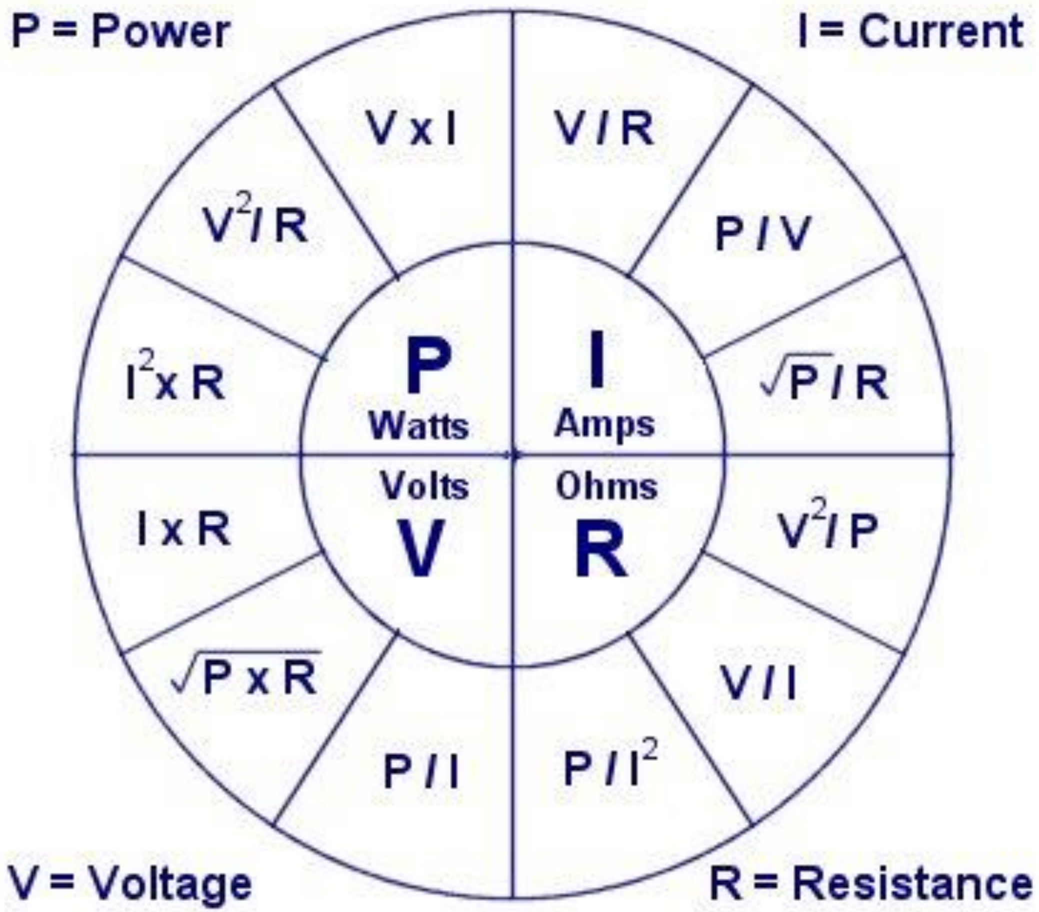
Watt's Law

- Description
  - Relates the power of a circuit as a function of the voltage and current of the circuit
- Formula
  - $P = V \cdot I = I^2R$
- Example
  - $P = (V_1 - V_2) \cdot I$
  - $P = (5V - 3V) \cdot (0.010A)$
  - $P = 0.02W$



Watt's Law (cont.)

- Relationship of Voltage, Current, and Resistance



Power Dissipation

When the voltage across a resistor forces current through it, the resistor gets **hot**. We need to make sure that the resistor is not damaged by too much heat. So resistors also have a power rating to indicate their limit.

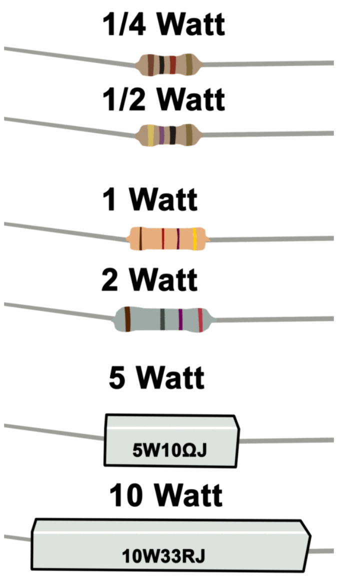
- Running current through a resistor dissipates power.

$$p = vi = i^2R = \frac{v^2}{R}$$

- The power dissipated is a non-linear function of current or voltage
- Power dissipated is always positive.
- A resistor can never generate power.

Resistor with Different Power Ratings

When the voltage across a resistor forces current through it, the resistor gets **hot**. We need to make sure that the resistor is not damaged by too much heat. So resistors also have a power rating to indicate their limit.



All resistors have a **Maximum Dissipated Power Rating**, which is the maximum amount of power it can safely dissipate without damage to itself.

Resistors which exceed their maximum power rating tend to go up in smoke, usually quite quickly, and damage the circuit they are connected to.

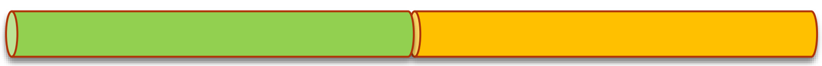
Type	Power Rating	Stability
Metal Film	Very low at less than 3 Watts	High 1%
Carbon	Low at less than 5 Watts	Low 20%
Wirewound	High up to 500 Watts	High 1%

Two 100Ω resistors will have the same resistance but one rated at 1W will be able to handle more voltage and current than one rated at ½W.

A 200Ω, ½ watt and a 200Ω, 5 watt resistor will have exactly the same influence on a circuit. It is just that a 5 watt resistor can withstand more voltage and current than a ½ watt resistor.

Case-1: 3 tubes of same diameter and length L:

Case-2: 2 tubes of same diameter and length L:



Serially Connected

Case-3: 1 tubes of same diameter and length L

What will be total amount of water passing through these setups for a unit time?

Case-4: 2 tubes of same diameter and length L

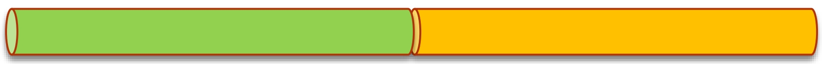
Case-5: 3 tubes of same diameter and length L

Parallelly Connected

Tubes and water: Reflection

Case-1: 3 tubes of same diameter and length L:

Case-2: 2 tubes of same diameter and length L:



Serially Connected

Case-3: 1 tubes of same diameter and length L

Case-5: Will have highest water delivered.

Case-1: will have highest back pressure

Case-4: 2 tubes of same diameter and length L

Case-5: 3 tubes of same diameter and length L

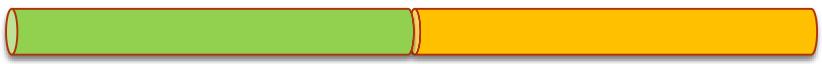
Parallelly Connected

Combining Resistors

Case-1: 3 copper wires of same diameter and length L:

$$R_{eq} = \rho\frac{L}{A} + \rho\frac{L}{A} + \rho\frac{L}{A}. = \rho\frac{3L}{A}$$

Case-2: 2 copper wires of same diameter and length L:



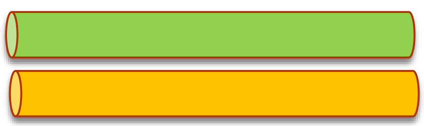
$$R_{eq} = \rho\frac{L}{A} + \rho\frac{L}{A} = \rho\frac{2L}{A}$$

Serially Connected

Case-3: 1 1 copper wire of same diameter and length L

$$R_{eq} = \rho\frac{L}{A}$$

Case-4: 2 copper wires of same diameter and length L



$$R_{eq} = \rho\frac{L}{2A}$$

Parallelly Connected

Case-5: 3 copper wires of same diameter and length L

$$R_{eq} = \rho\frac{L}{3A}$$

Combining Resistors

What does this model show about resistors in series?

Adding resistors in series **increases** overall resistance

What does this model show about resistors in parallel?

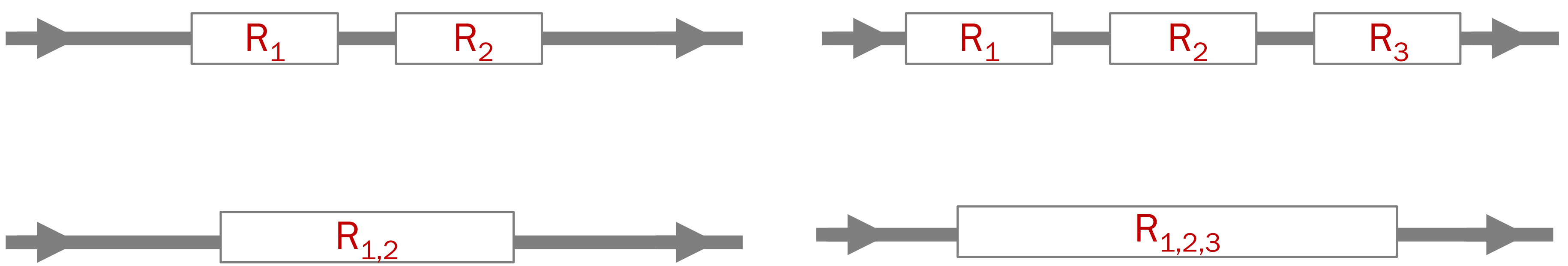
Adding resistors in parallel **decreases** overall resistance

Combining Resistors: Series

When combining resistors in series, the resistances are simply added up as if they were one large resistor

$$R_{total} = R_1 + R_2 + \cdots$$

$$R_{total} = \rho\frac{L1}{A} + \rho\frac{L2}{A} + \rho\frac{L}{A} \quad \dots \dots .$$



Equivalent Resistance for Resistors in Series

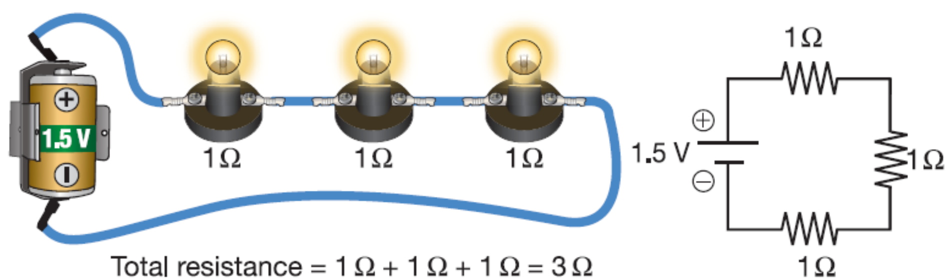
$$\text{equivalent resistance} = \text{resistance } 1 + \text{resistance } 2 + \text{resistance } 3 + \cdots$$

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

SI unit: ohm (Ω)

ADDING RESISTANCES IN A SERIES CIRCUIT

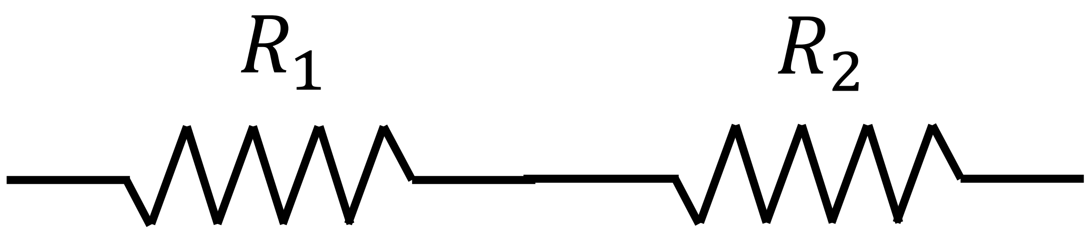
$$\underbrace{R_{total}}_{\text{Total resistance }(\Omega)} = \underbrace{R_1 + R_2 + R_3}_{\text{Individual resistances }(\Omega)} + \ldots$$



Total resistance = 1 Ω + 1 Ω + 1 Ω = 3 Ω

Resistors in series/parallel

- If two resistors are connected in series, what is the total resistance?



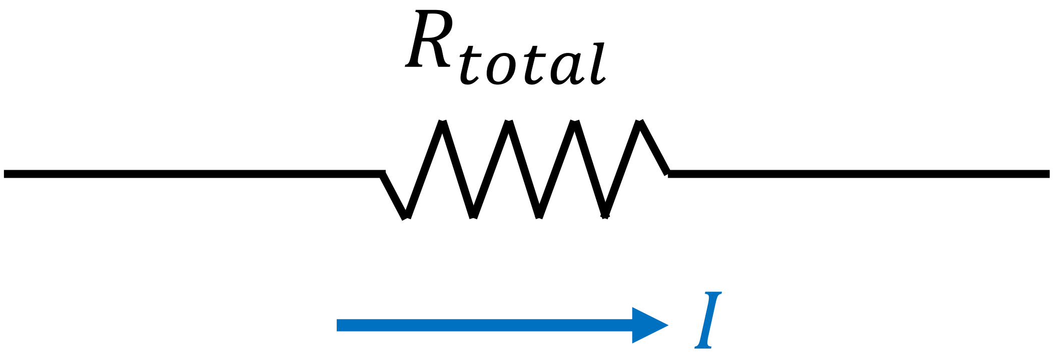
same current $\longrightarrow I$ $\qquad \longrightarrow I$

Potential drop $V_1 = I\,R_1$ $\qquad$ Potential drop $V_2 = I\,R_2$

Total potential drop $V = V_1 + V_2 = I\,R_1 + I\,R_2 = I\,(R_1 + R_2)$

Resistors in series/parallel

- If two resistors are connected in series, what is the total resistance?



Potential drop $V = I\,R_{total} = I\,(R_1 + R_2)$

$$\boxed{R_{total} = R_1 + R_2}$$

- Total resistance increases in series!

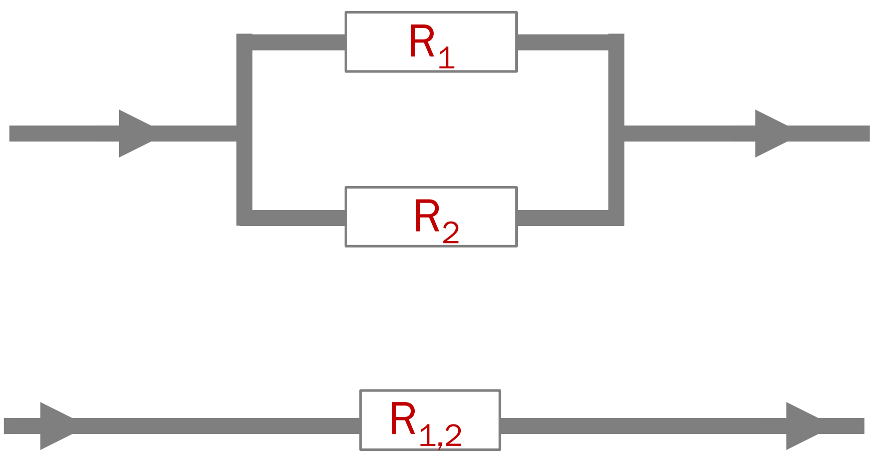
Combining Resistors: Parallel

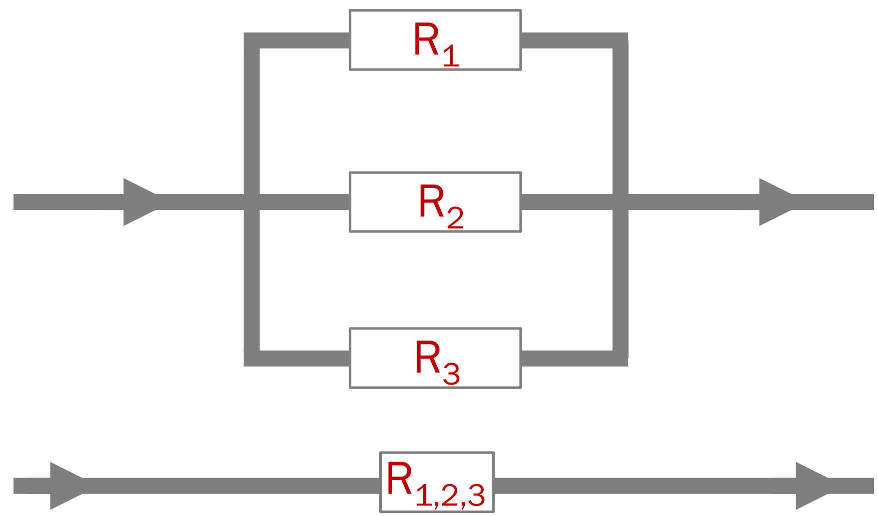
When combining resistors in parallel, the overall resistance decreases to produce a smaller equivalent resistance

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots$$

$${R_{total}}^{-1} = \left({R_1}^{-1} + {R_1}^{-1} + \cdots\right)$$

$$R_{total} = \left({R_1}^{-1} + {R_1}^{-1} + \cdots\right)^{-1}$$





Combining Resistors: Parallel

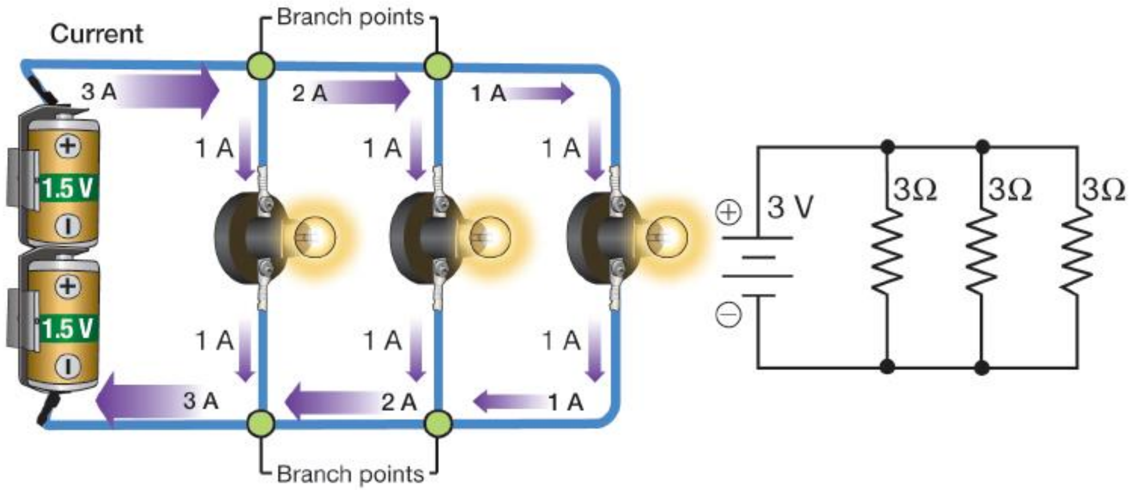
- In *parallel* circuits the current can take more than one path.

Equivalent Resistance for Resistors in Parallel

$$\frac{1}{\text{equivalent resistance}} = \frac{1}{\text{resistance 1}} + \frac{1}{\text{resistance 2}} + \frac{1}{\text{resistance 3}} + \cdots$$

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

SI unit: ohm (Ω)



Examples

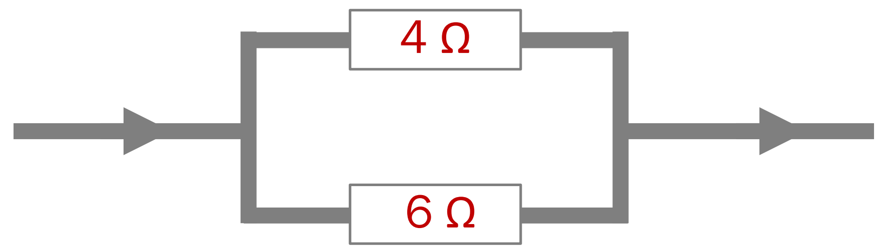
Series

$$R_{total} = R_1 + R_2 + \cdots$$

$$4\,\Omega + 6\,\Omega + 8\,\Omega = \mathbf{18\,\Omega}$$

Parallel

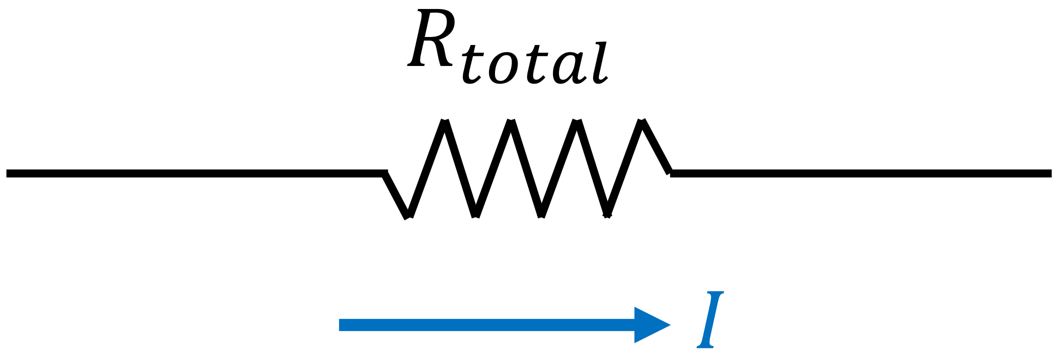
$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots$$



$$\frac{1}{4\,\Omega} + \frac{1}{6\,\Omega} = \frac{1}{\mathbf{2.4\,\Omega}}$$

Resistors in series/parallel

- If two resistors are connected in parallel, what is the total resistance?



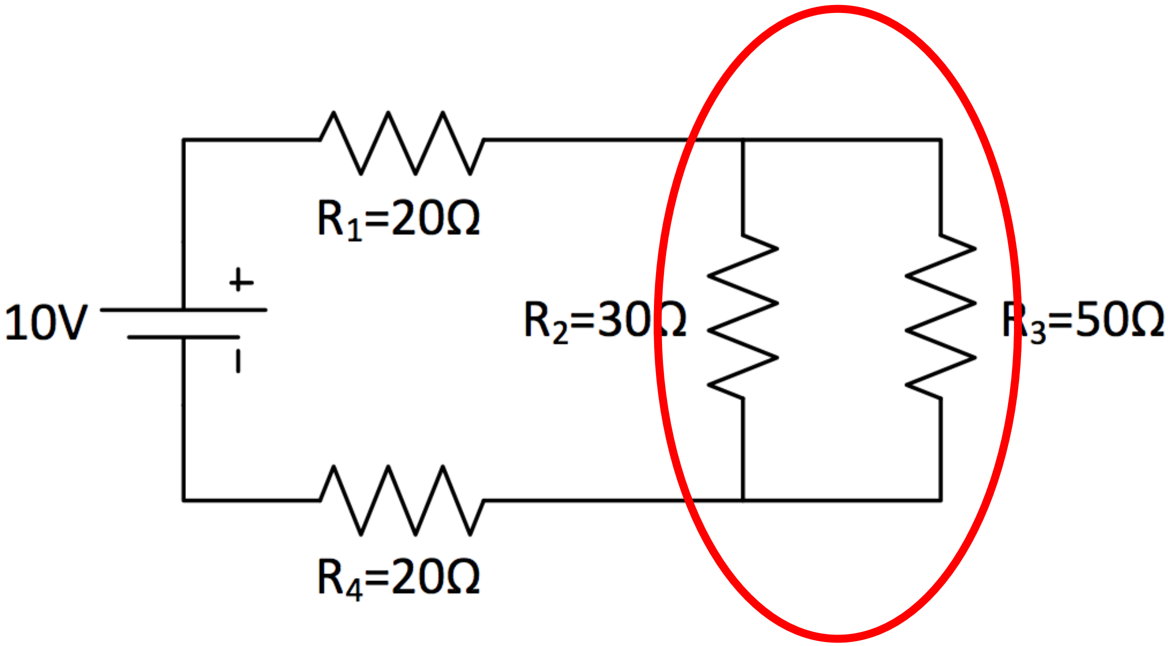
Current $I = \frac{V}{R_{total}} = V\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$

$$\boxed{\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2}}$$

- Total resistance decreases in parallel!

Resistors in series/parallel

- What's the current flowing?



(1) Combine these 2 resistors in parallel:

$$\frac{1}{R_{pair}} = \frac{1}{30} + \frac{1}{50}$$

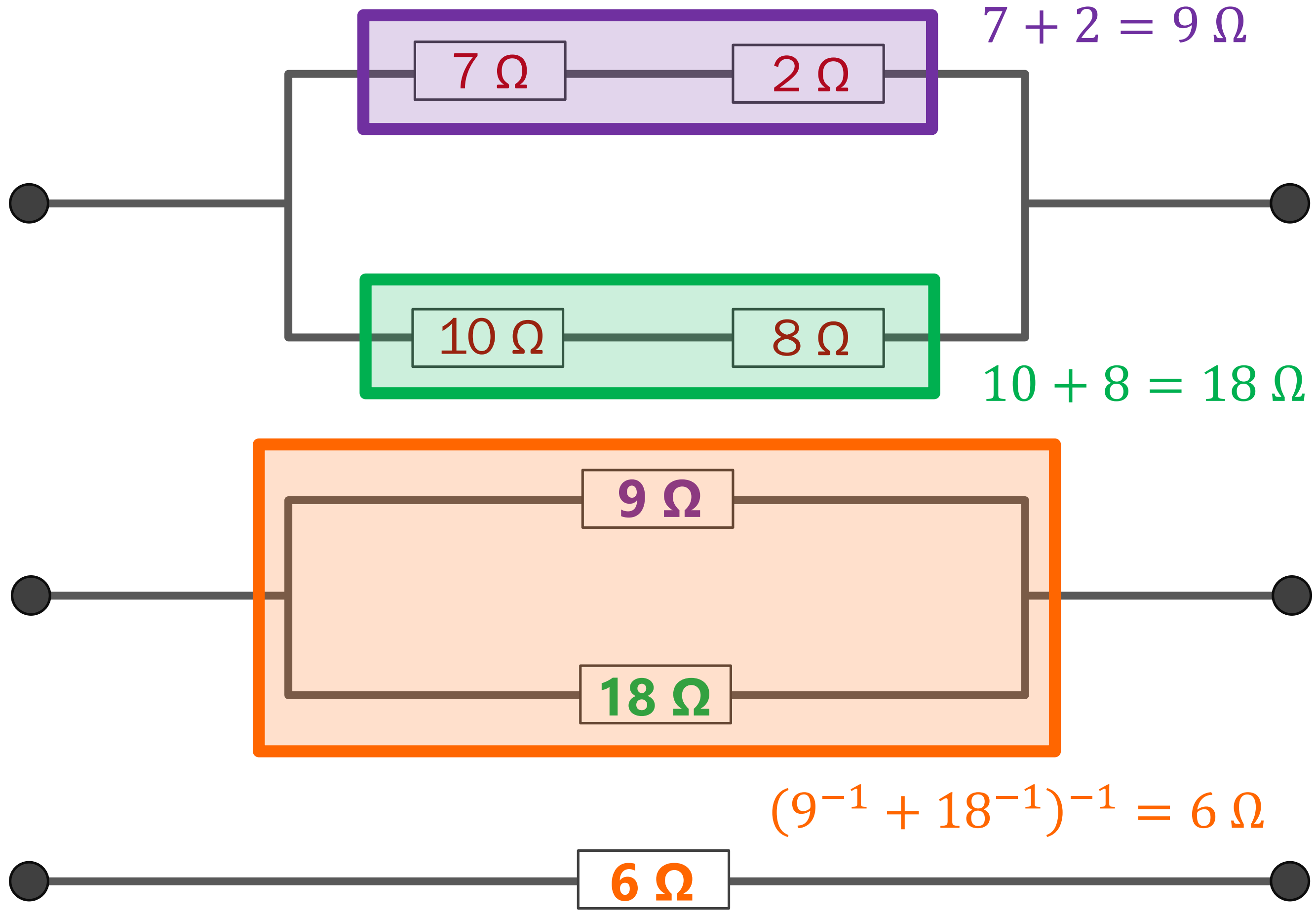
$$R_{pair} = 18.75\ \Omega$$

(2) Combine all the resistors in series:

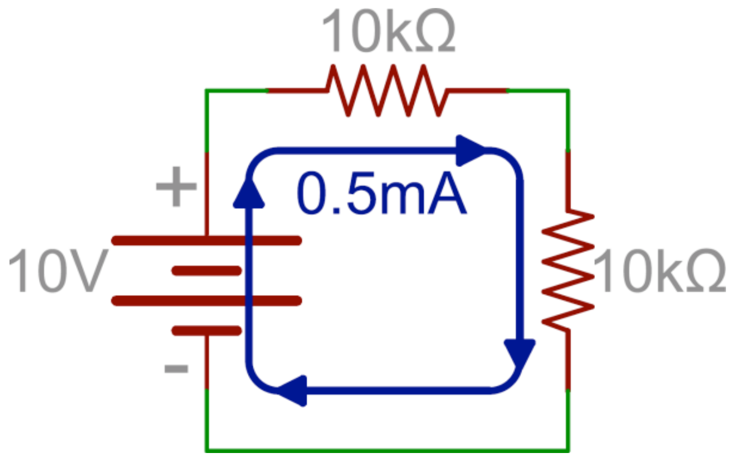
$$R_{total} = 20 + 18.75 + 20 = 58.75\ \Omega$$

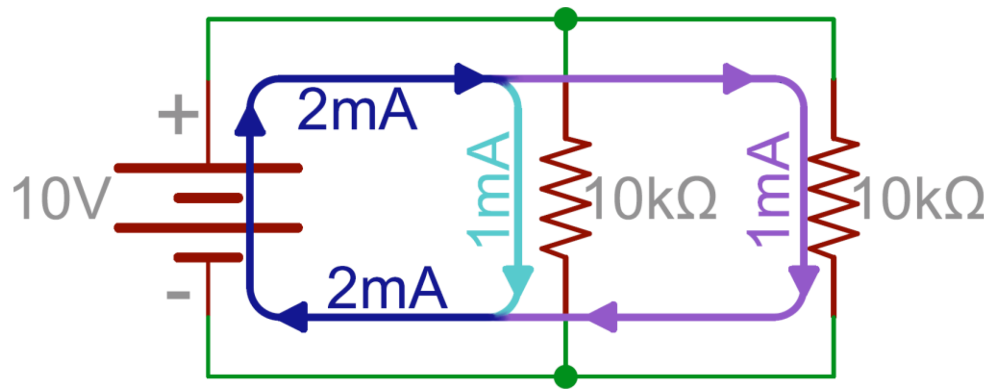
(3) Current $I = \frac{V}{R_{total}} = \frac{10}{58.75} = 0.17\ A$

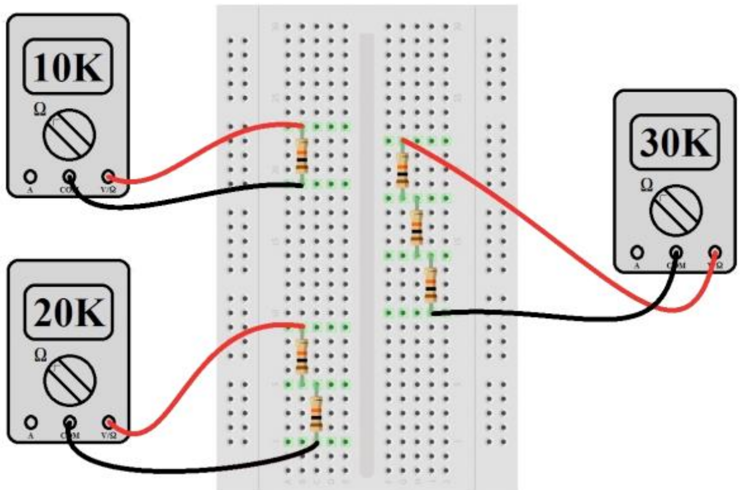
Examples

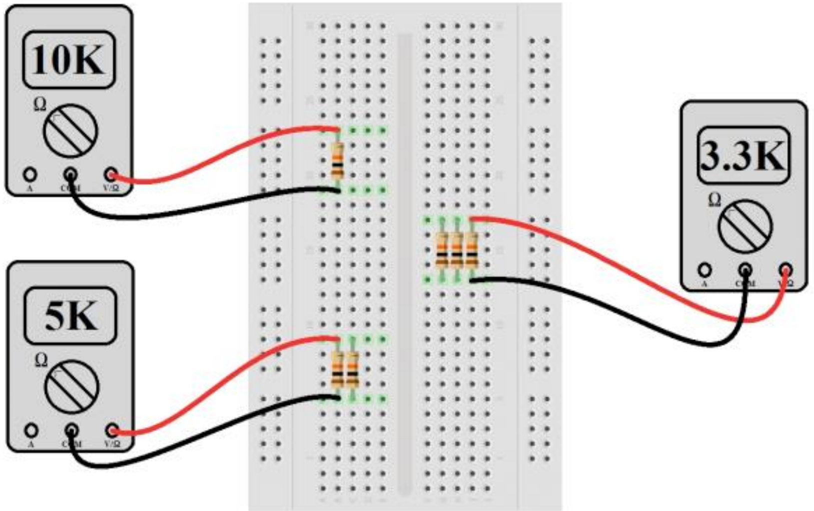


Resistor Connections







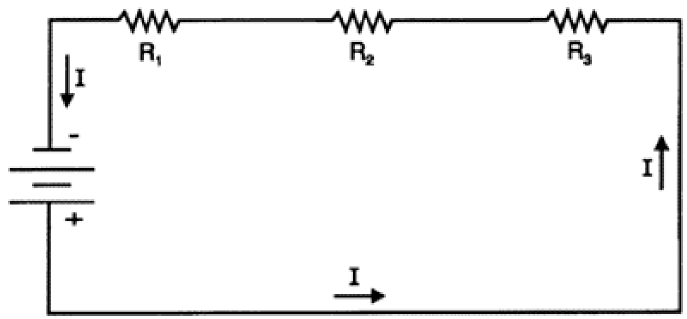


$$R_{tot} = R_1 + R_2 + ... + R_{N-1} + R_N$$

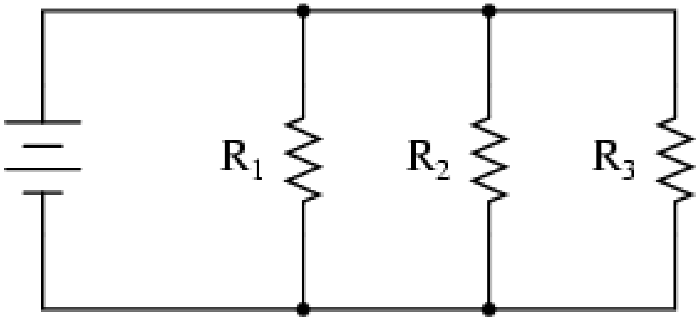
$$\frac{1}{R_{tot}} = \frac{1}{R_1} + \frac{1}{R_2} + ... + \frac{1}{R_{N-1}} + \frac{1}{R_N}$$

Series vs. Parallel

Series



Parallel



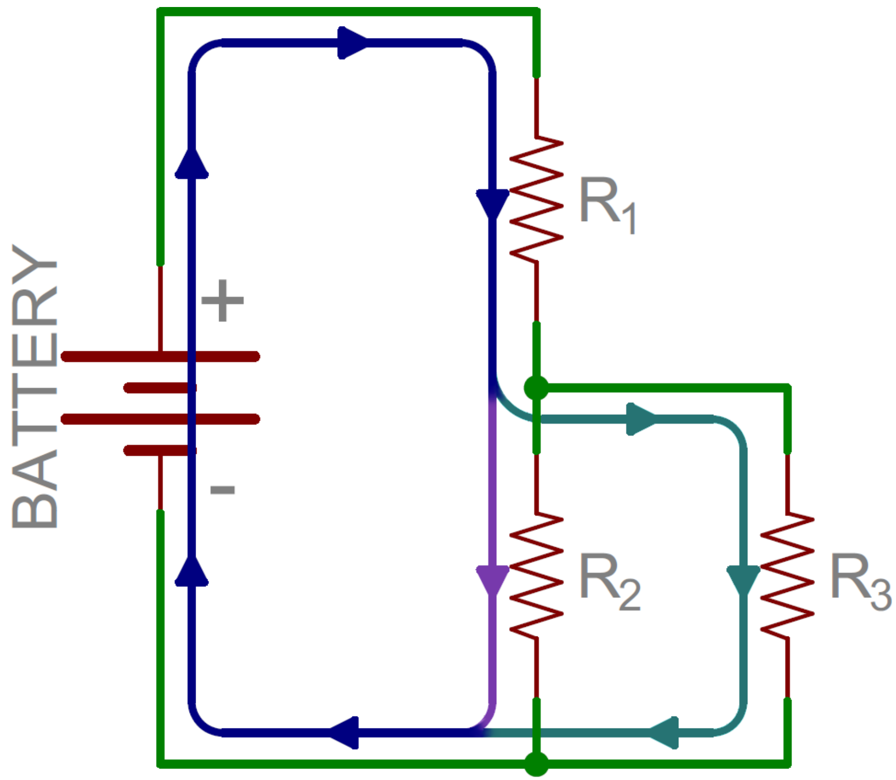
	Series	Parallel
CURRENT	Same current through all series elements	Current "splits up" through parallel branches
VOLTAGE	Voltages add to total circuit voltage	Same voltage across all parallel branches
RESISTANCE	Adding resistance increases total R	Adding resistance reduces total R

Combination of Resistors

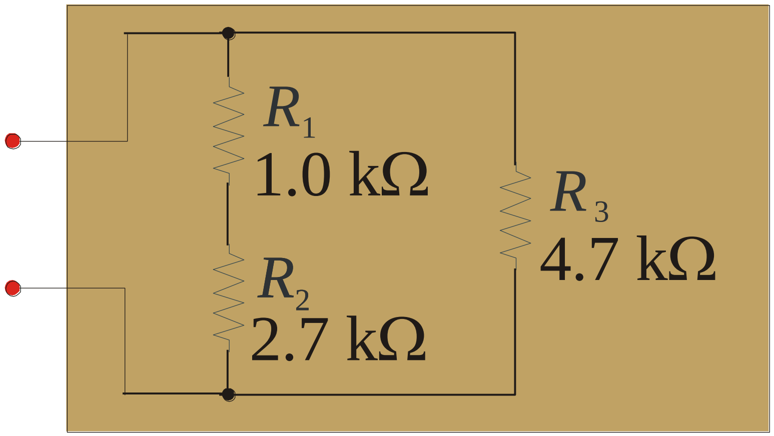
- Most practical circuits have combinations of series and parallel components.
- An important analysis method is to form an equivalent circuit.
- An equivalent circuit is one that has characteristics that are electrically the same as another circuit but is generally simpler.

Series and Parallel Circuits Working Together

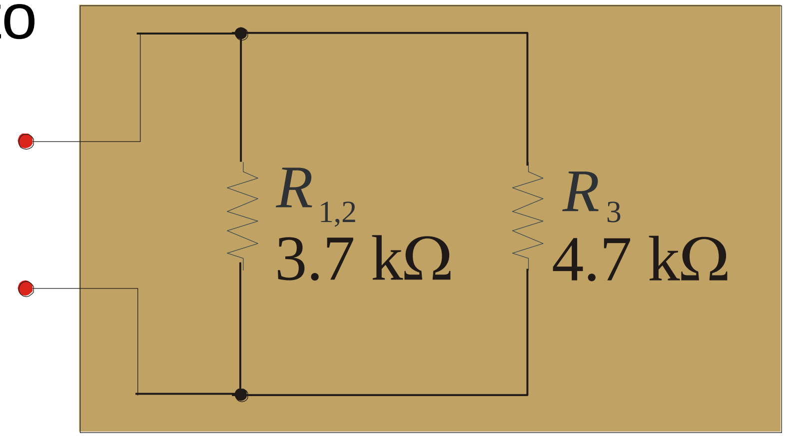
- From the positive battery terminal, current first encounters R1. But, at the other side of R1 the node splits, and current can go to both R2 and R3. The current paths through R2 and R3 are then tied together again, and current goes back to the negative terminal of the battery.



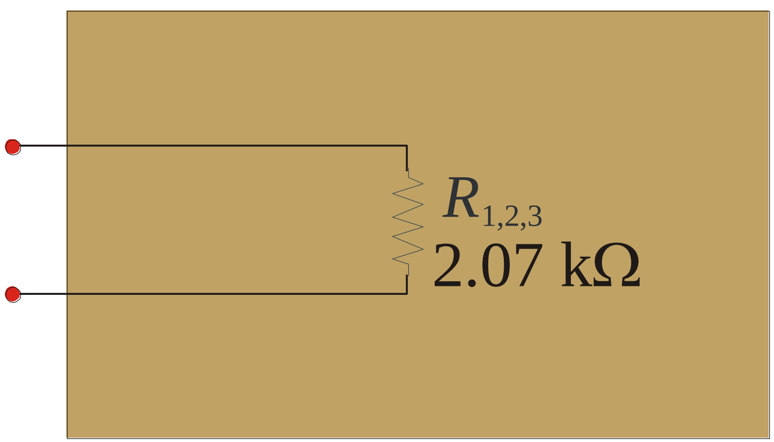
Series and Parallel Circuits



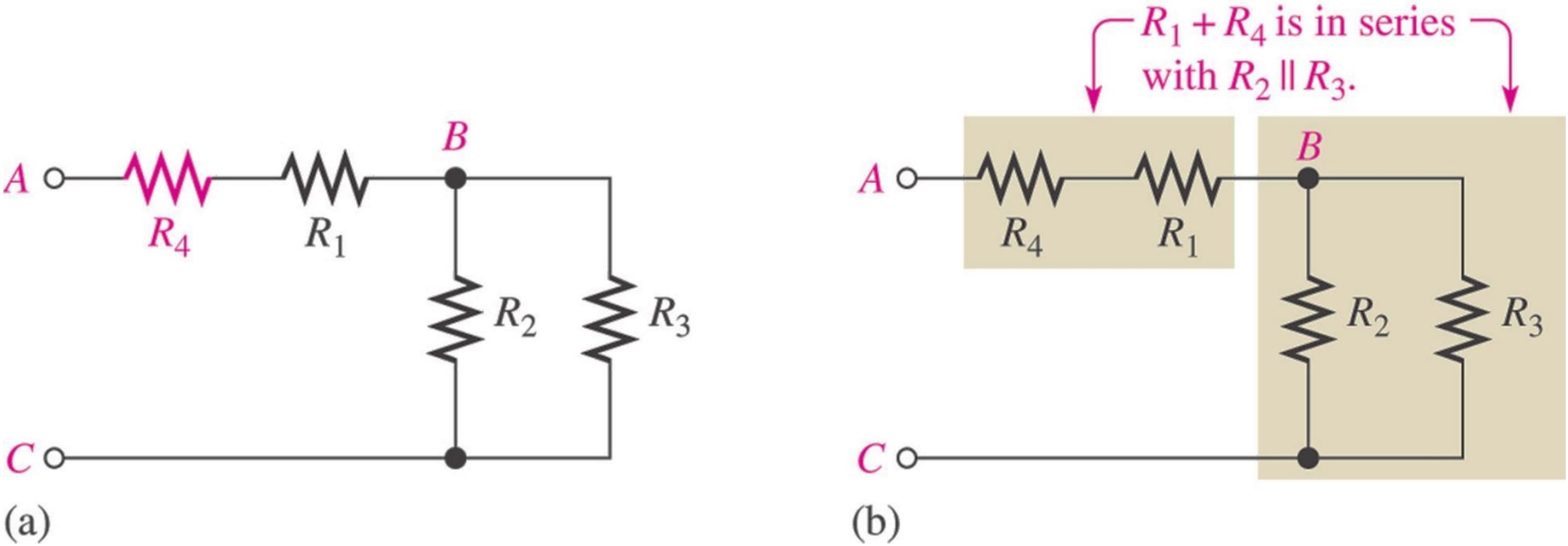
is equivalent to



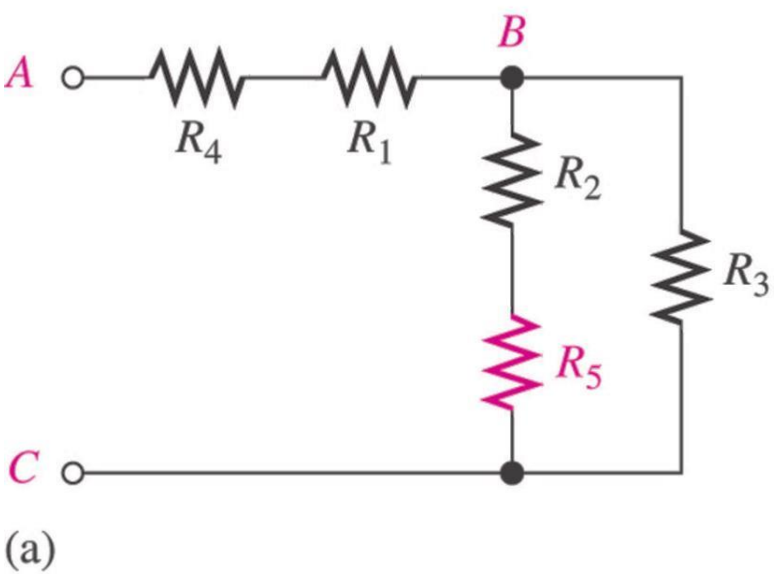
is equivalent to

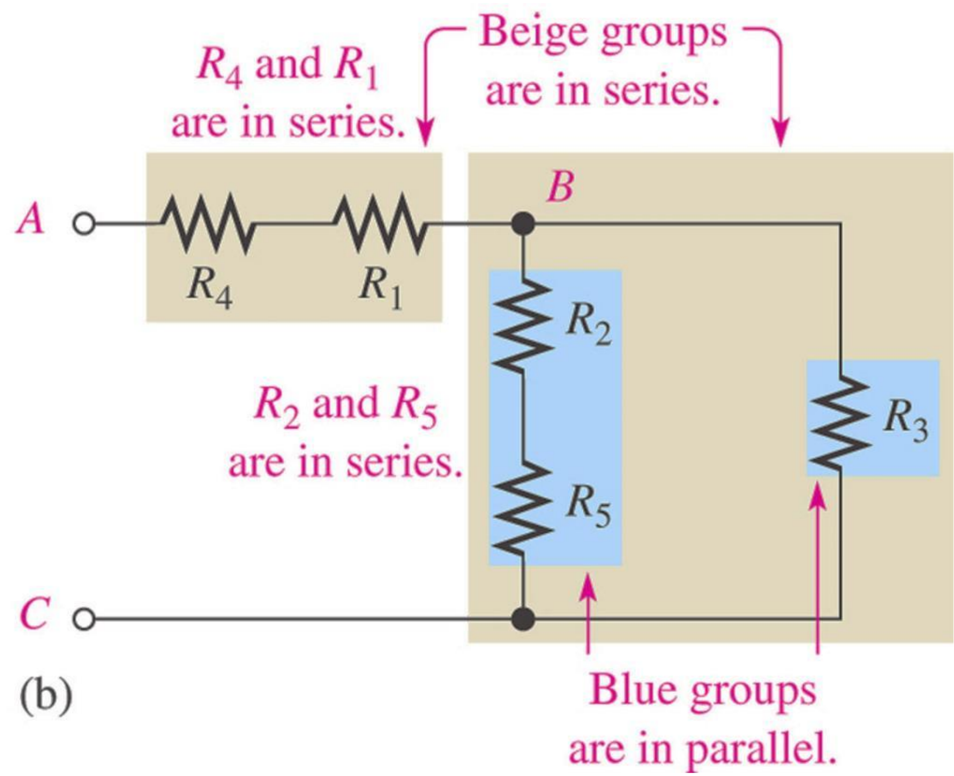


Series and Parallel Circuits

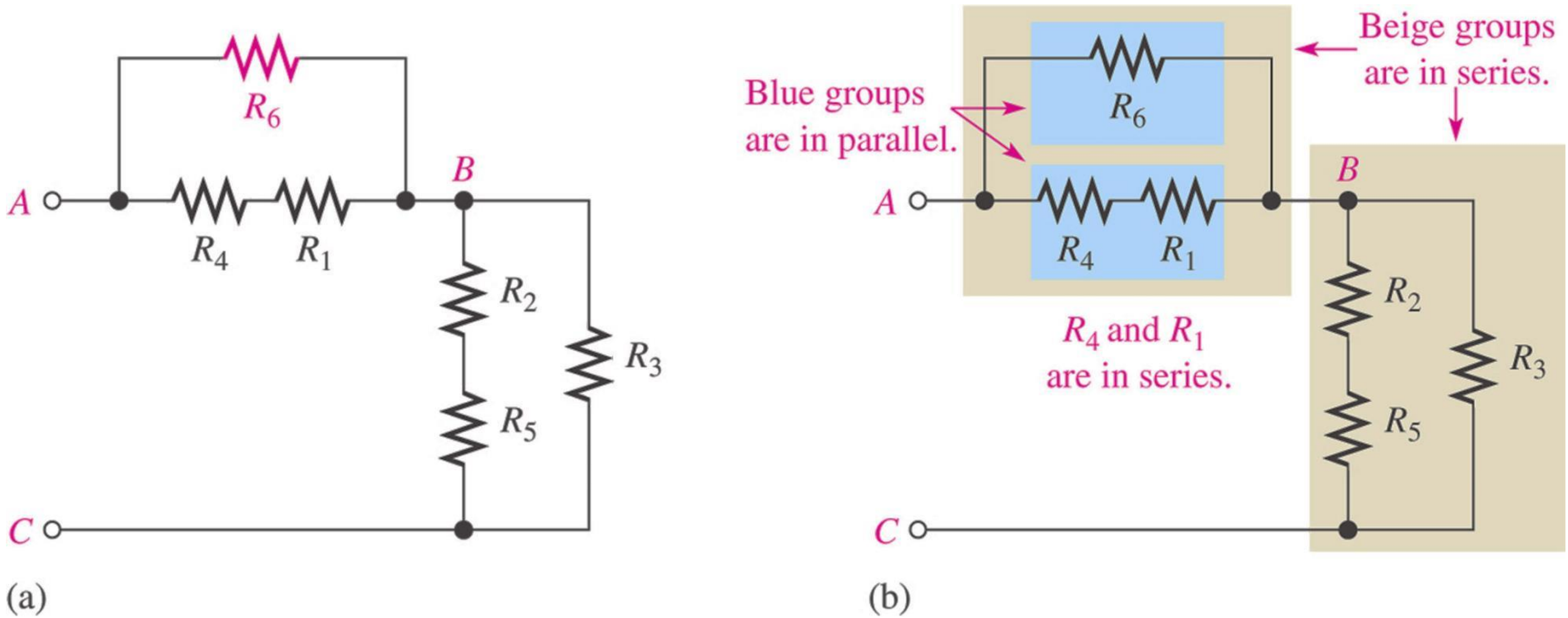


Series and Parallel Circuits



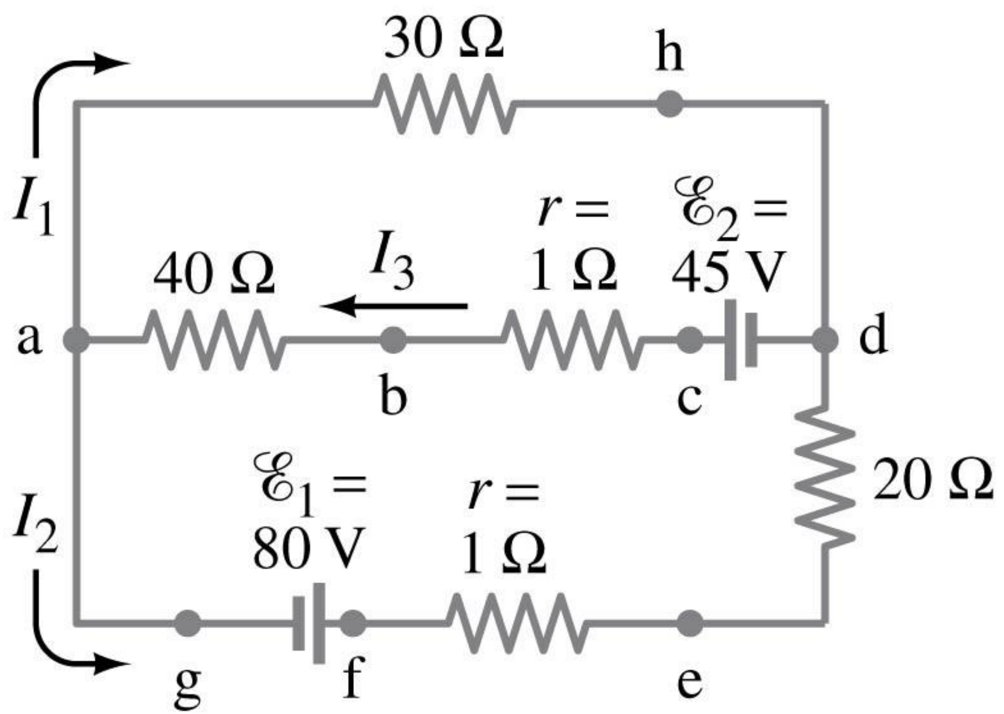


Series and Parallel Circuits



Kirchhoff's Rules

Some circuits cannot be broken down into series and parallel connections.



For these circuits we use Kirchhoff's rules.

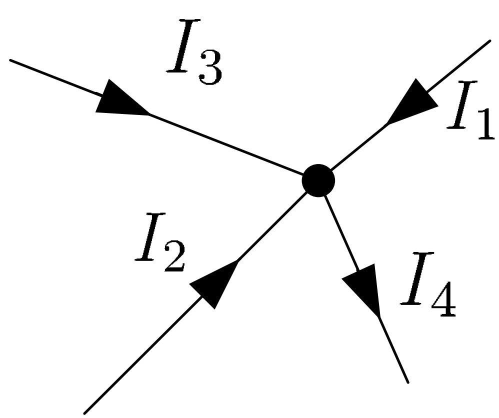
Junction rule: The sum of currents entering a junction equals the sum of the currents leaving it.

Kirchhoff's Law

- Descriptions
  - Indicates that the sum of the potential differences through the circuit must be zero (Voltage Law)
  - Indicates that the sum of the currents from a wire branch must be equal to the input current (Current Law)
- Formulas
  - $\Sigma V = 0$
  - $I_s = I_1 + I_2 + \ldots + I_n$
- Examples
  - $I = V/R$
  - $R_r = R_1 + R_2$
  - $R_r = 12k\Omega$
  - $I = (5V - 0V)/12k\Omega = 4.167 \cdot 10^{-4} A$
  - $V_a = 5V - I \cdot R_1$
  - $V_a = 5V - (4.167 \cdot 10^{-4} A) \cdot 2k\Omega = 4.167V$

- Two important theorems for circuit analysis

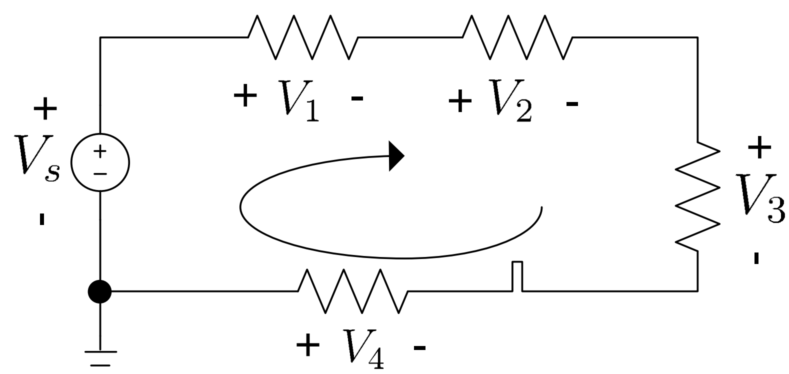
Kirchhoff's current law (KCL)



$$I_1 + I_2 + I_3 - I_4 = 0$$

Net current entering a **node** = 0

Kirchhoff's voltage law (KVL)



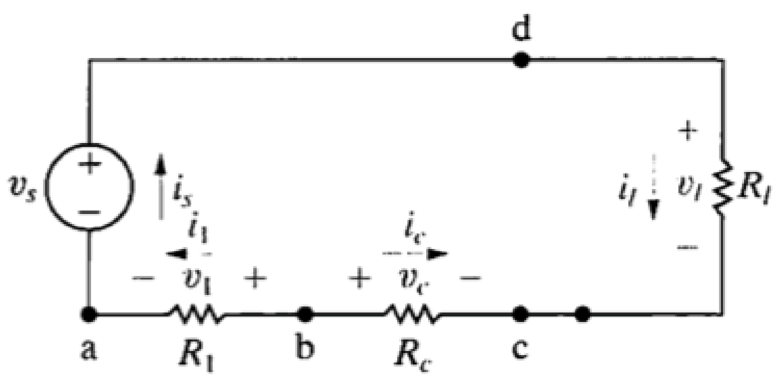
$$-V_s + V_1 + V_2 + V_3 - V_4 = 0$$

Net voltage in a **loop** = 0

(CAUTION: mind the direction/sign of current and voltage)

Kirchhoff's current law (KCL)

- Kirchoff's current law is based on conservation of charge
- It states that the algebraic sum of currents entering a node (or a closed boundary) is zero.
- It can be expressed as: $$\sum_{n=1}^{N} i_n = 0$$
- The algebraic sum of all the currents at any node in a circuit equals zero.



node a $\quad i_s - i_1 = 0,$

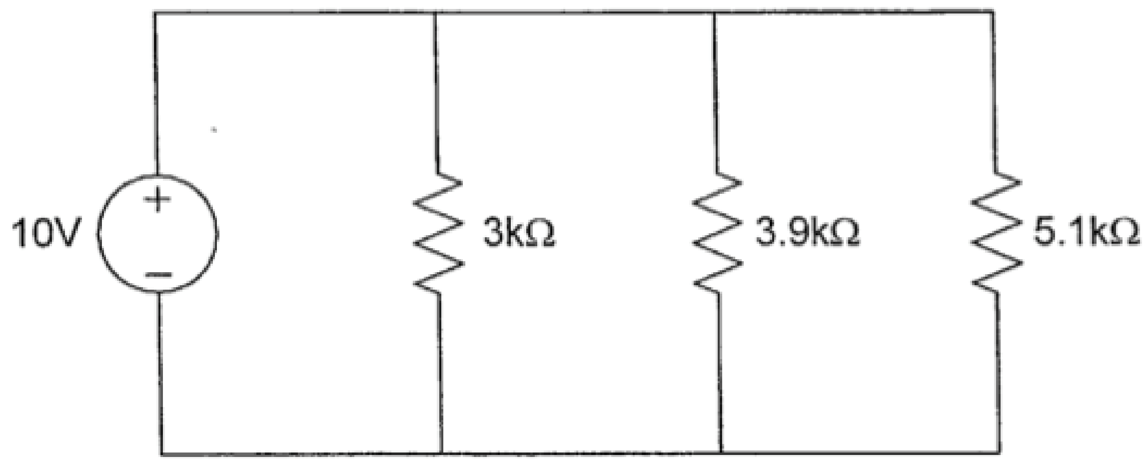
node b $\quad i_1 + i_c = 0,$

node c $\quad -i_c - i_l = 0,$

node d $\quad i_l - i_s = 0.$

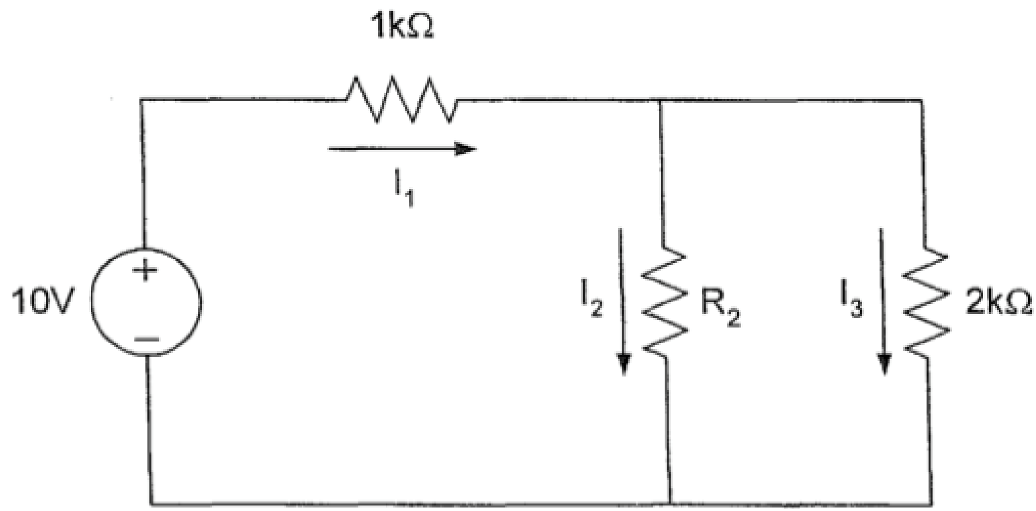
- Using the convention that currents leaving the node are considered positive and that entering the nodes are considered negative, the above circuit yields the four equations.

Procedure-Equivalent Resistance



- Set up the circuit as shown in figure.
- Adjust the output of the DC power supply to 10V.
- Measure and record the total current into the circuit.
- Using the measured current and voltage, determine the equivalent resistance of the parallel components in the circuit.
- Replace the resistors with a resistance substitution box set to the equivalent resistance and measure the current as before.
- Compare the experimentally determined equivalent resistance to the theoretical value.

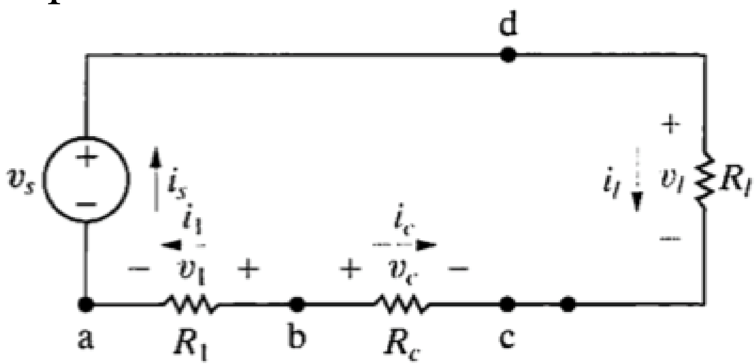
- Set up the circuit as shown in figure.
- Adjust the output of the DC power supply to 10V.
- Begin with R_2=510Ω and measure the currents I_1, I_2 and I_3.
- Repeat with R_2=1kΩ, 2kΩ, 3kΩ, 4.3kΩ and 5.1kΩ.
- Compare the measured currents to those calculated using current divider relation.
- Determine whether or not each set of measurements agrees with KCL.



Kirchhoff's Voltage Law (KVL)

- Kirchoff's voltage law is based on conservation of energy
- It states that the algebraic sum of currents around a closed path (or loop) is zero.
- It can be expressed as: $$\sum_{m=1}^{M} v_m = 0$$

- The algebraic sum of all the voltages around any closed path in a circuit equals zero.

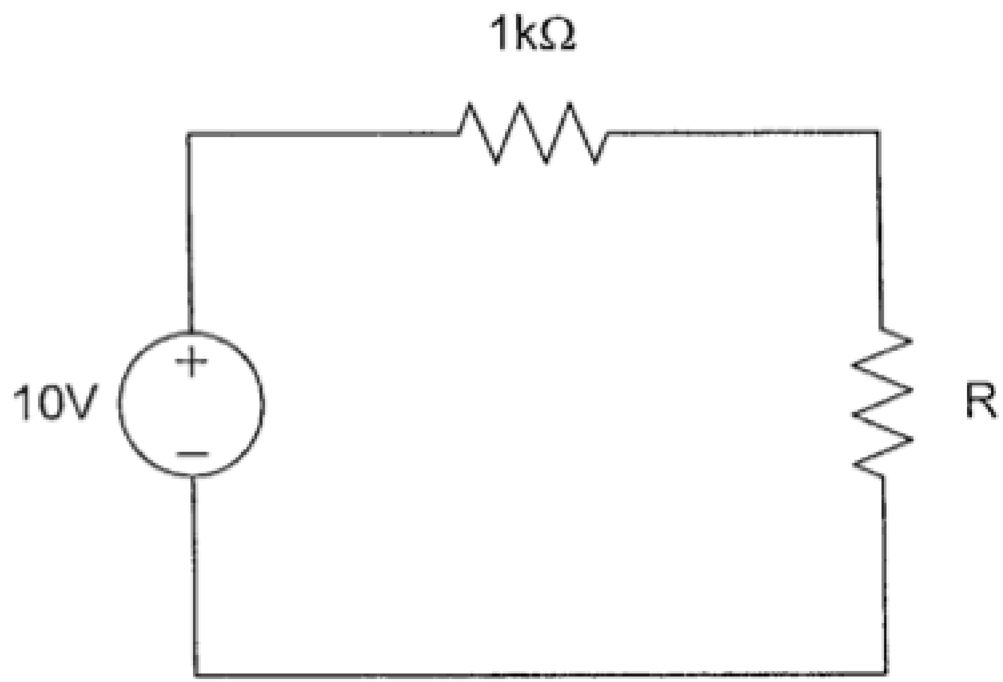


$$v_l - v_c + v_1 - v_s = 0$$

- Here we elect to trace the closed path clockwise, assigning a positive algebraic sign to voltage drops.
- Starting at node d leads to the expression:

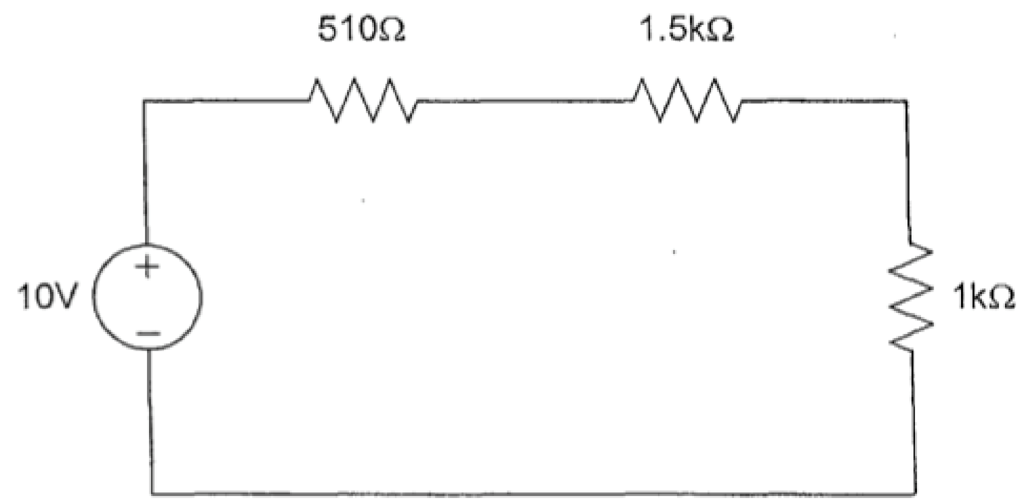
Procedure-Voltage Division

- Set up the circuit as shown in figure.
- Adjust the output of the DC power supply to 10V.
- Begin with R=510Ω and measure the voltage across each resistor.
- Repeat with R=1kΩ, 2kΩ, 3kΩ, 4.3kΩ and 5.1kΩ.
- Compare the measured voltages to those calculated using the voltage divider relation.



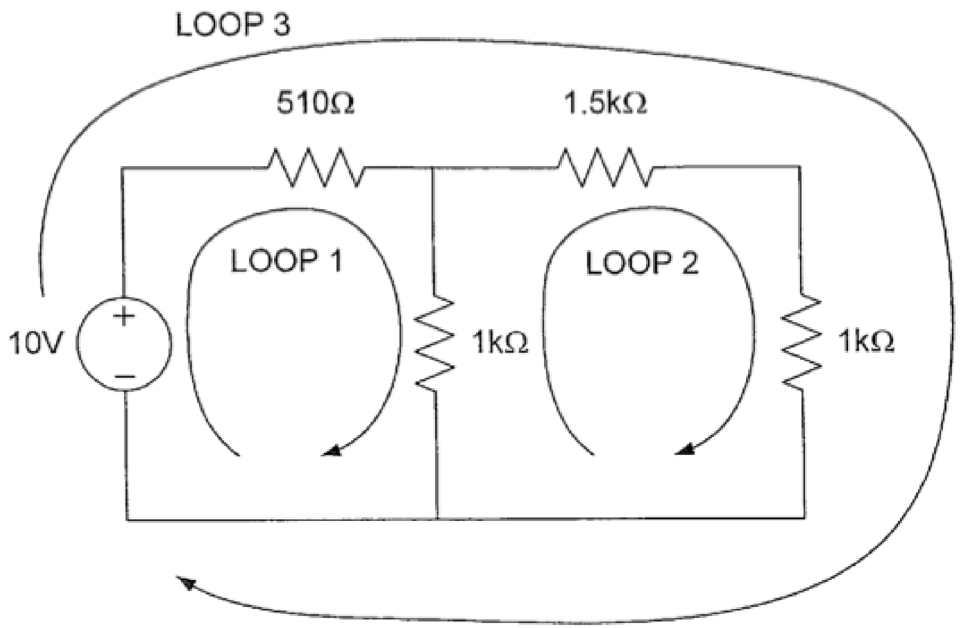
Procedure-Kirchhoff's Voltage Law (KVL) (Single Loop)

- Set up the circuit as shown in figure.
- Adjust the output of the DC power supply to 10V.
- Measure the voltage across each component.
- Compare the measured voltages to those calculated using the voltage divider relation.
- Determine whether or not your measurements agree with KVL.



Procedure-Kirchhoff's Voltage Law (KVL) (Multiple Loops)

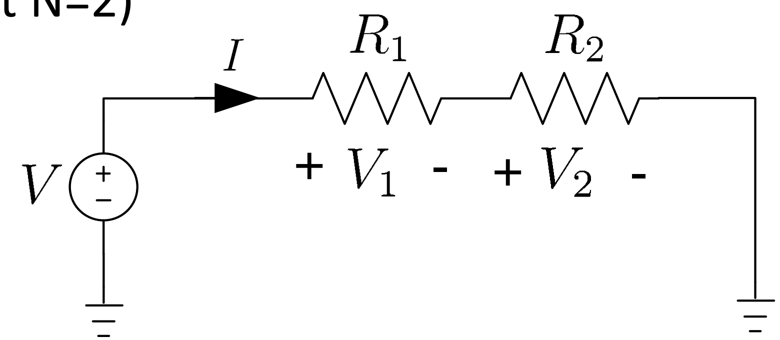
- Set up the circuit as shown in figure.
- Adjust the output of the DC power supply to 10V.
- Measure the voltage across each component in loop 1.
- Repeat for loop 2 and 3.
- Compare your measured values with the terms in the KVL equation written for each loop.
- Determine whether or not your measurements agree with KVL.



Application -- voltage divider

- We probably don't need something as complex as the last example

- Consider the resistors in series again: (let N=2)



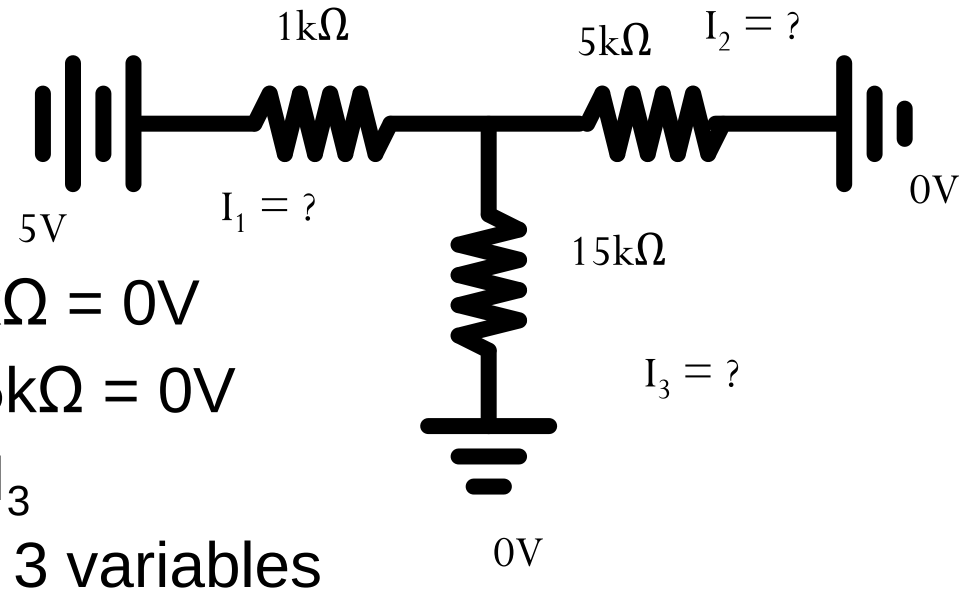
- The supplied voltage *V* is **divided** into two parts

$$I = \frac{V}{R_{eqv}} = \frac{V}{R_1 + R_2} \implies V_1 = \frac{R_1}{R_1 + R_2} \cdot V, \;\; V_2 = \frac{R_2}{R_1 + R_2} \cdot V$$

- This principle is called the **Voltage Divider**

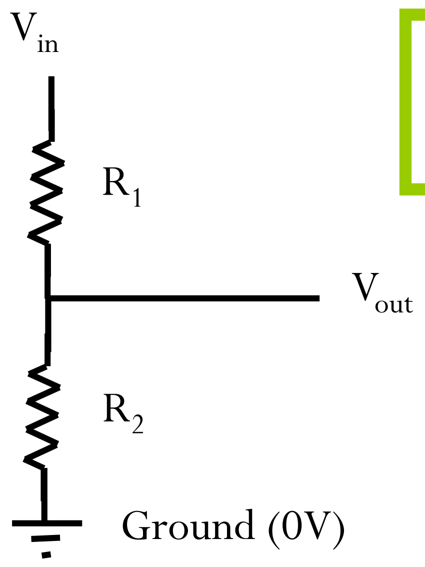
Kirchhoff's Law (cont.)

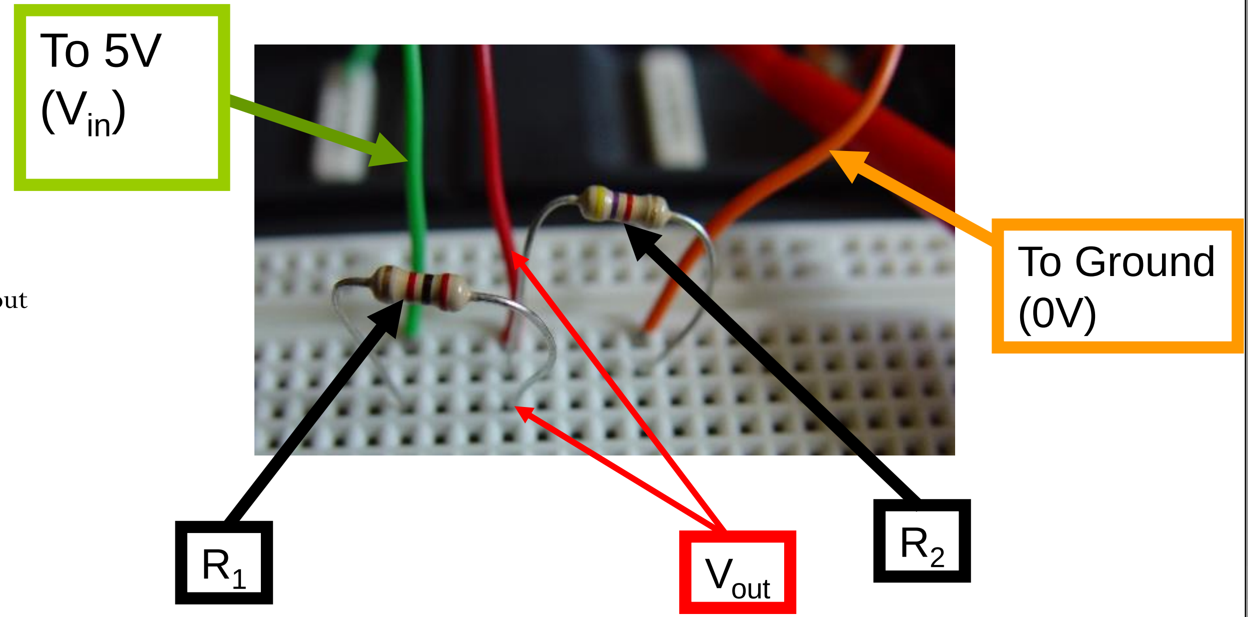
- Examples
  - $\Sigma V = 0$
  - $5V - I_1 \cdot 1k\Omega - I_2 \cdot 5k\Omega = 0V$
  - $5V - I_1 \cdot 1k\Omega - I_3 \cdot 15k\Omega = 0V$
  - $I_1 = I_2 + I_3$, $I_2 = I_1 - I_3$
  - 3 linear equations, 3 variables
  - $I_1 = 1.053$ mA
  - $I_2 = 0.789$ mA
  - $I_3 = 0.264$ mA



Voltage Divider

- Suppose you have a fixed voltage power supply (V_{in}).
- To generate a voltage V_{out} (between 0 and V_{in}): Build a "voltage divider"
- using resistors (R_1, R_2, R_3.....).

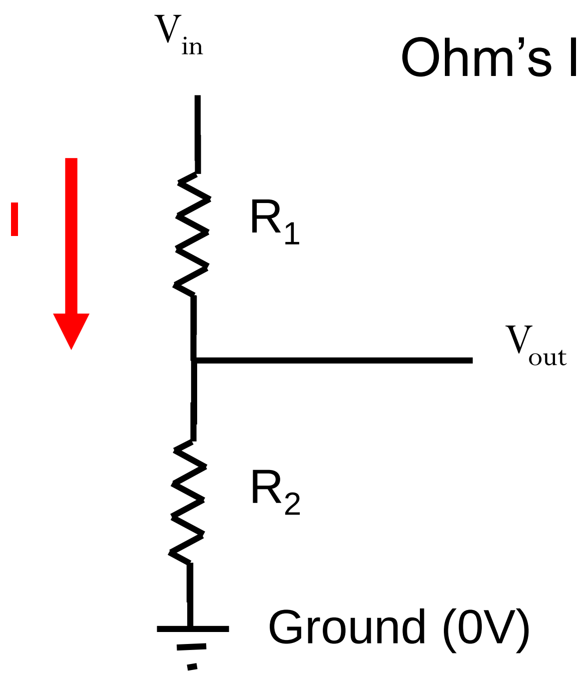




Voltage Divider

The total resistance of the circuit is: $R_{total} = R_1 + R_2$ (1)

→ The current from V_{in} to ground is: $$I = \frac{V_{in} - 0}{R_1 + R_2} \quad (2)$$

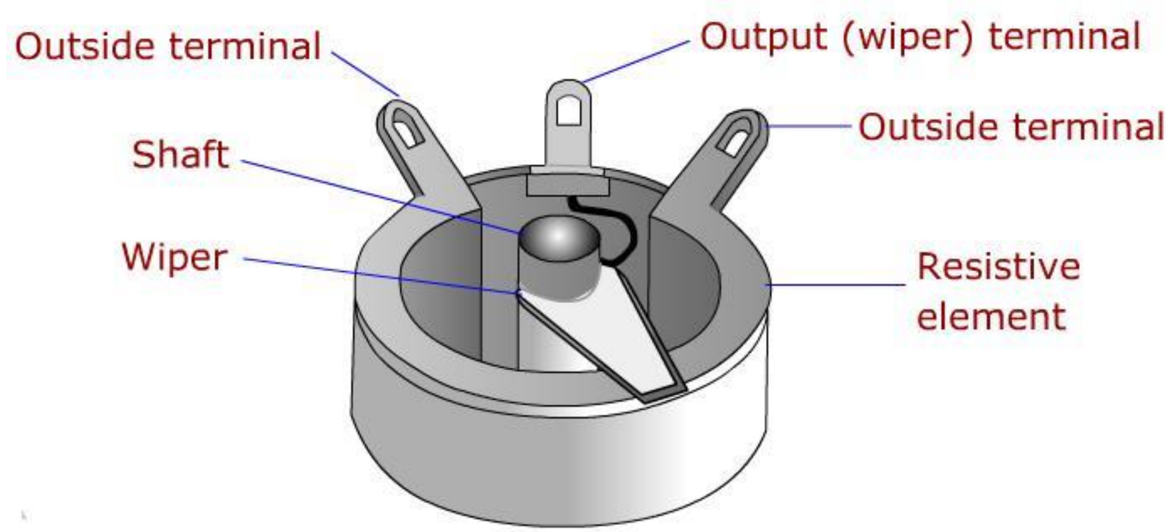


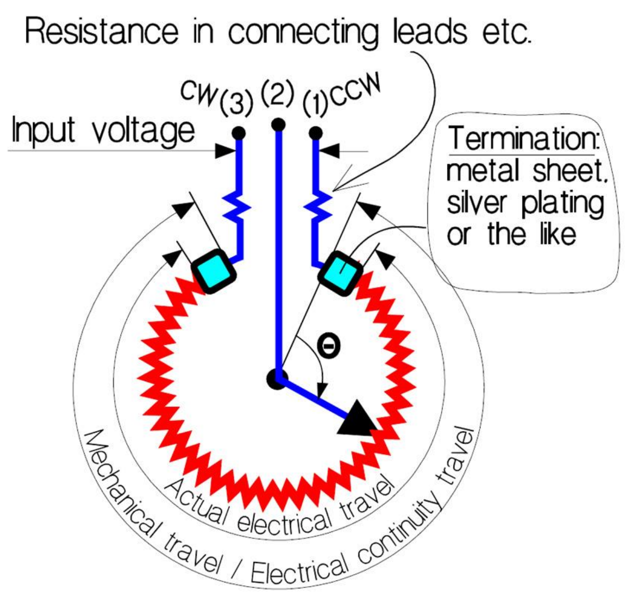
Ohm's law for R_2: $$V_{out} - 0V = R_2 I \quad (3)$$

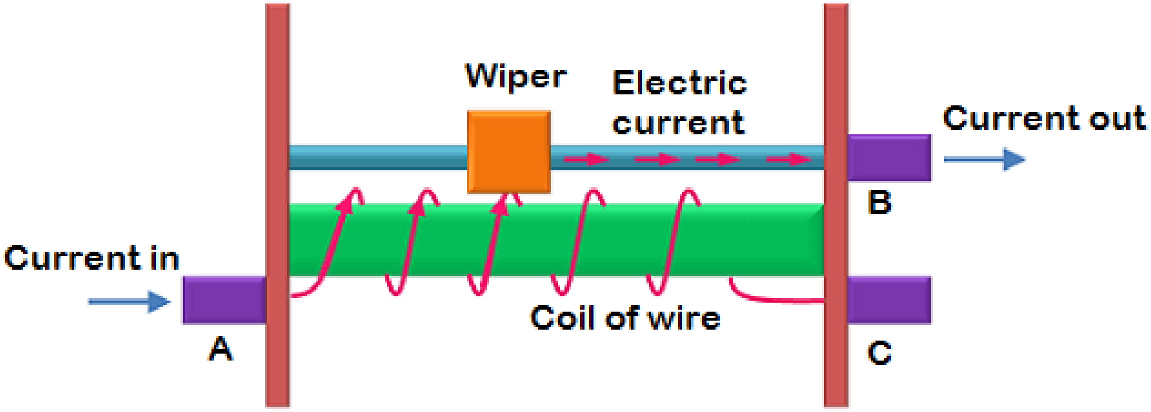
Combining (2) and (3):

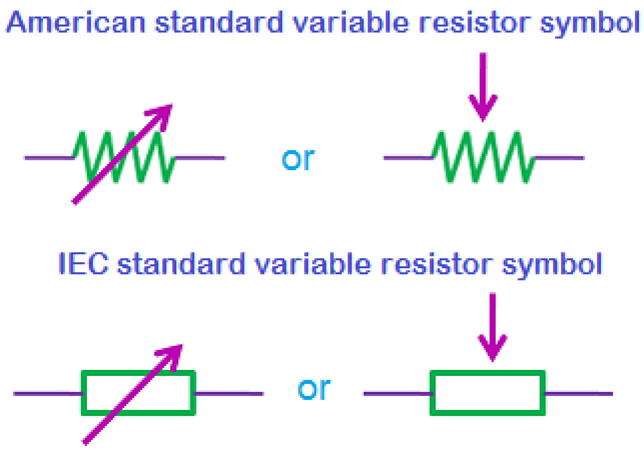
$$\boxed{V_{out} = V_{in} \frac{R_2}{R_1 + R_2}}$$

A variable Resistor





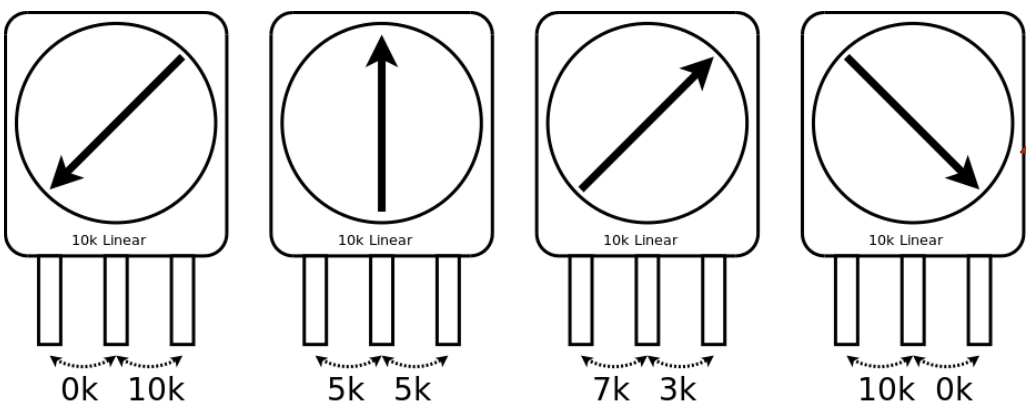




Potentiometer

A **potentiometer** is a much more useful form of **variable** resistor. In fact a variable resistor is, in reality, a potentiometer with one of the connections remaining unused.

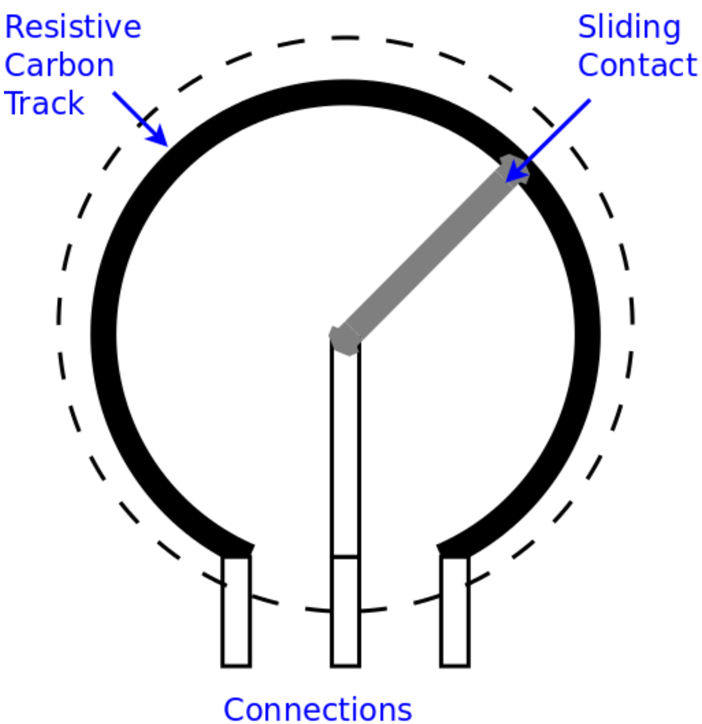
A potentiometer has **3 connections**. The resistance between the two outer connections is a **fixed** value. The resistances between the centre connection and each of the two outer connections is variable – but the two always **add up** to the same total resistance.

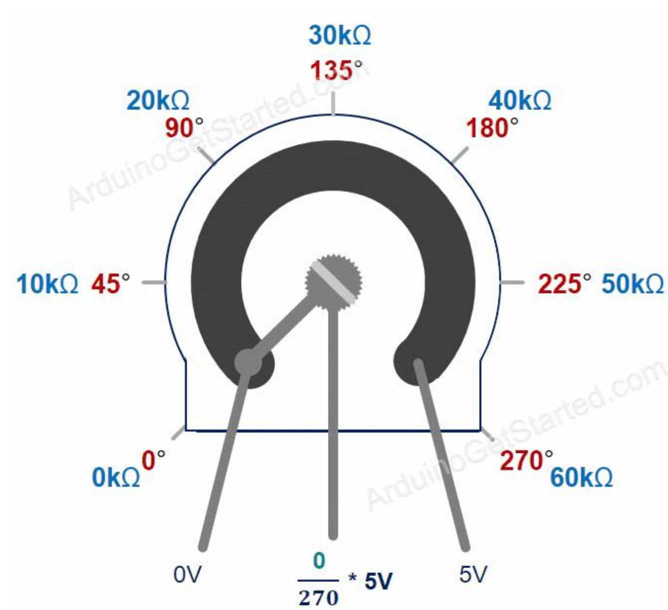


The resistance between the outer most terminals is always 10kΩ
The resistance between the centre terminal and the outer terminals always adds up to 10kΩ

Potentiometer

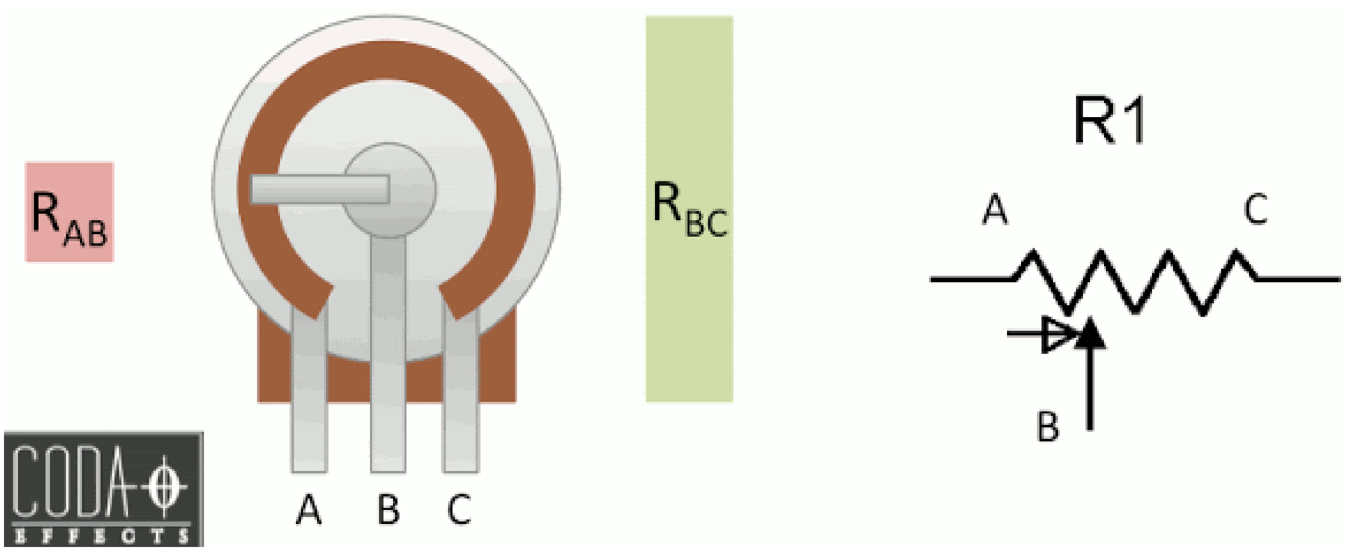
Inside a potentiometer a sliding contact moves along a carbon track (or a wire wound track) – the resistance of the track remains fixed but the resistance between the end and the sliding contact changes





A variable Resistor

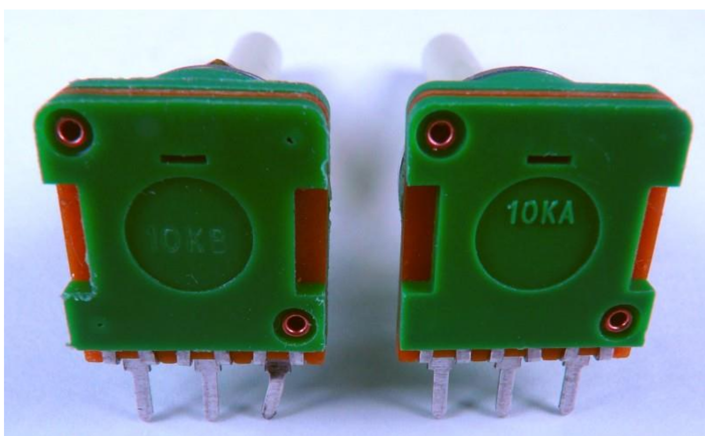
The carbon track is effectively a fixed value resistor and the sliding contact connects to a section of the carbon track. A potentiometer is effectively **two** resistors in **series** – as the value of one resistor increases, the other decreases to that their total remains constant.



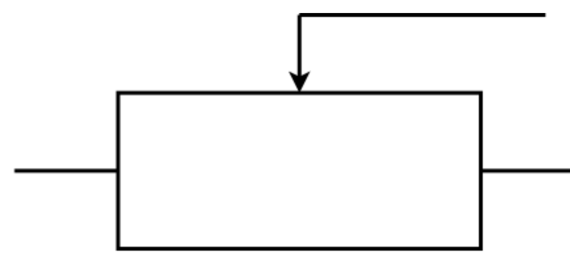
Potentiometer

The resistance of a rotary or linear potentiometer can either change linearly with position or logarithmically with position.

In the case of the logarithmic potentiometer ("log pot" for short), a small change in position results in a small change in resistance at one end of the track but the same small change of position results in a large change in resistance at the other end of the track.

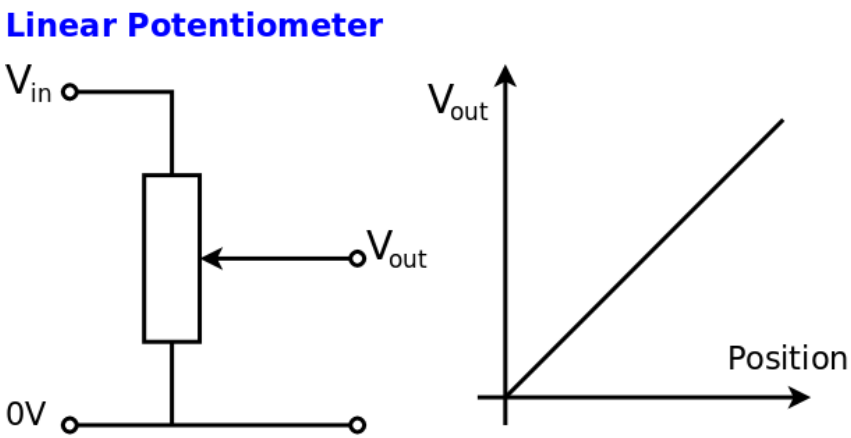


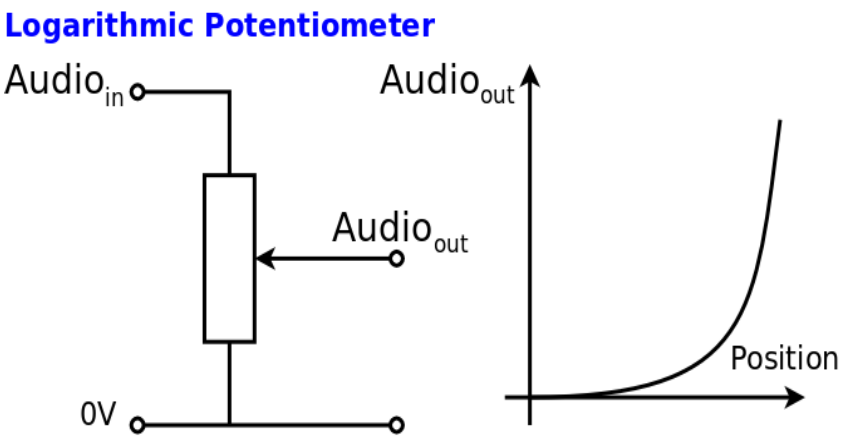
A Linear potentiometer is marked with a B
A Logarithmic potentiometer is marked with an A



Potentiometer

- The function of a potentiometer is to act as a potential divider. A potential difference is applied across the outer most connections. The inner connection is a fraction of the applied potential difference.
- This is useful in voltage supplies (Lin) and volume controls (Log)

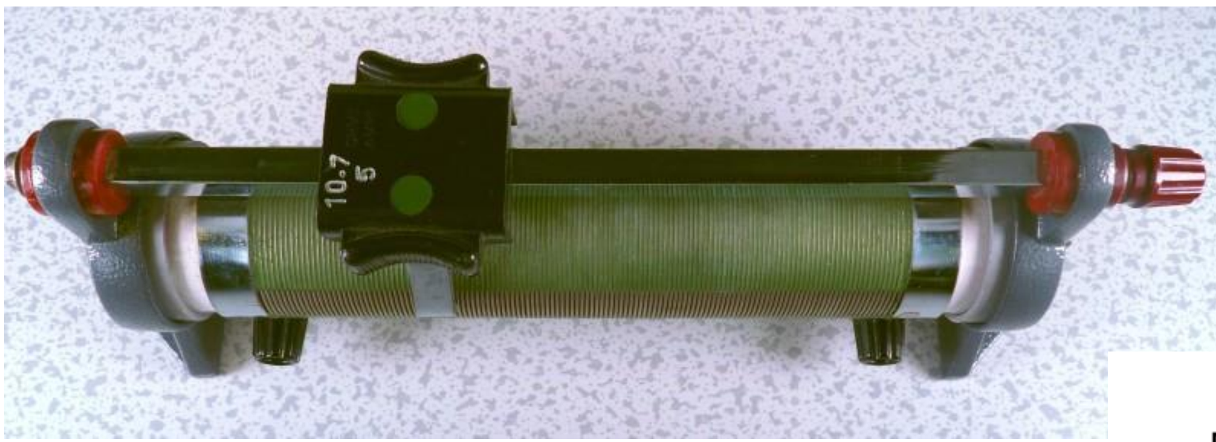


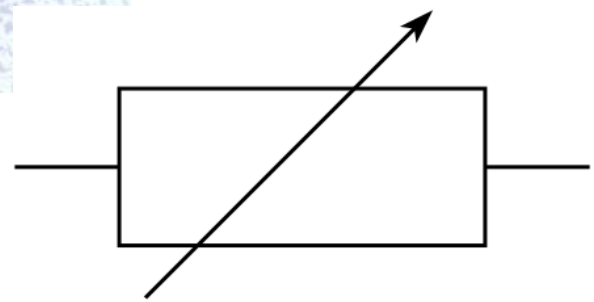


Rheostats

A rheostat is a potentiometer that can handle large currents. Therefore, a rheostat is a power version of a potentiometer.

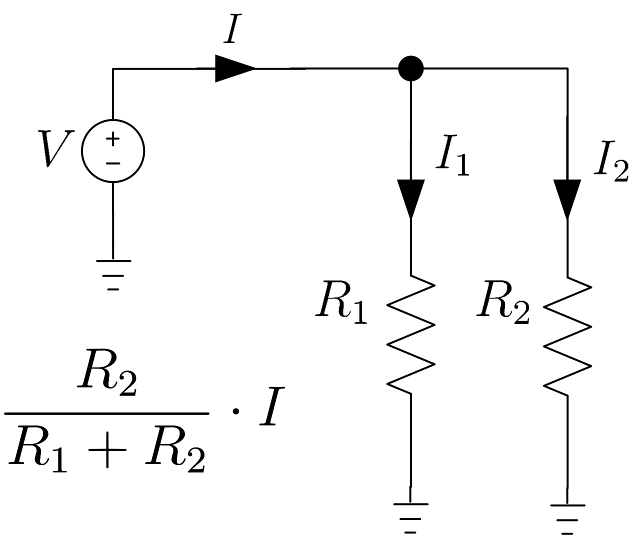
Rheostats are often used to limit current and are most often configured as a simple variable resistor.





Application – current divider

- Consider the resistors in parallel : (let N=2)



- The current *I* is **divided** into two parts

$$I = I_1 + I_2$$

$$I_1 = \frac{V}{R_1}$$

$$I_2 = \frac{V}{R_2}$$

$$\implies$$

$$I_1 = \frac{I \cdot R_{eqv}}{R_1} = \frac{R_2}{R_1 + R_2} \cdot I$$

$$I_2 = \frac{I \cdot R_{eqv}}{R_2} = \frac{R_1}{R_1 + R_2} \cdot I$$

- **More current** flows in the branch with **less resistance**

- This principle is called the **Current Divider**

Current Division

- When resistors are in parallel, the voltage drop across them is the same

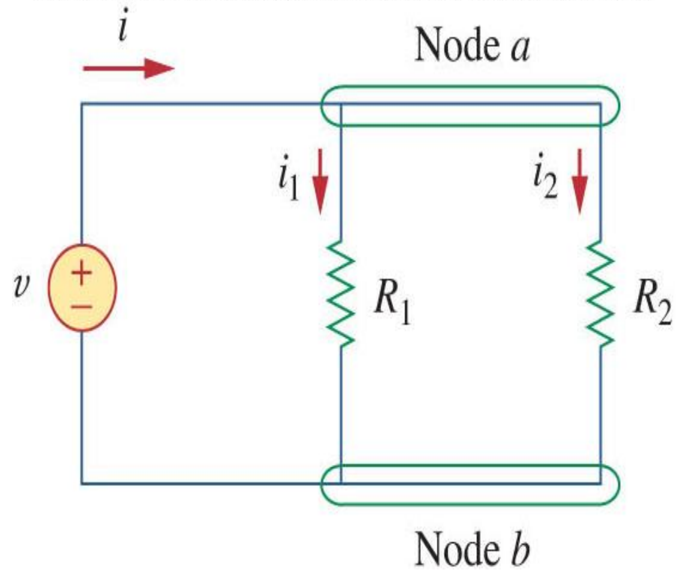
$$v = i_1 R_1 = i_2 R_2$$

- By KCL, the current at node *a* is

$$i = i_1 + i_2$$

- The equivalent resistance is:

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



Current Division

- Given the current entering the node, the voltage drop across the equivalent resistance will be the same as that for the individual resistors

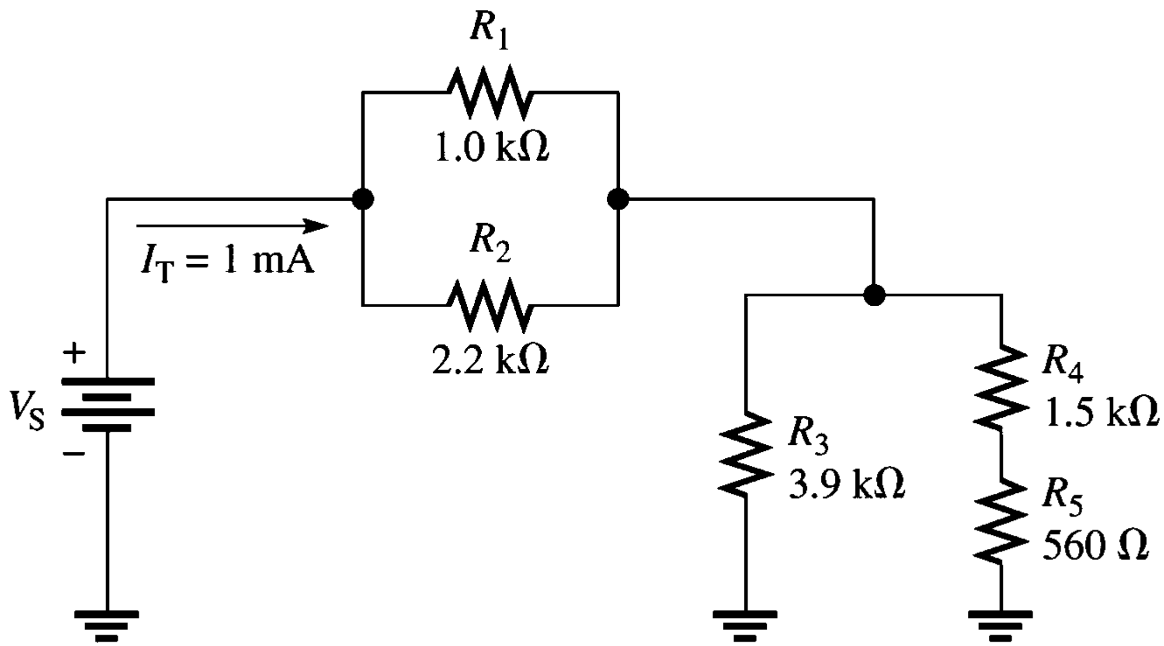
$$v = iR_{eq} = \frac{iR_1 R_2}{R_1 + R_2}$$

- This can be used in combination with Ohm's law to get the current through each resistor:

$$i_1 = \frac{iR_2}{R_1+R_2} \quad i_2 = \frac{iR_1}{R_1+R_2}$$

Series and Parallel Circuits

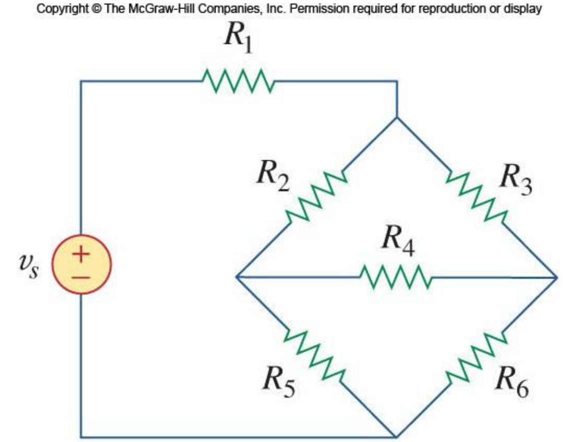
Determine the voltage drop across each resistor.



ANS: V_1 = 688 mV , V_2 = 688 mV , V_3 = 1.35 V , V_4 = 981 mV , V_5 = 366 mV

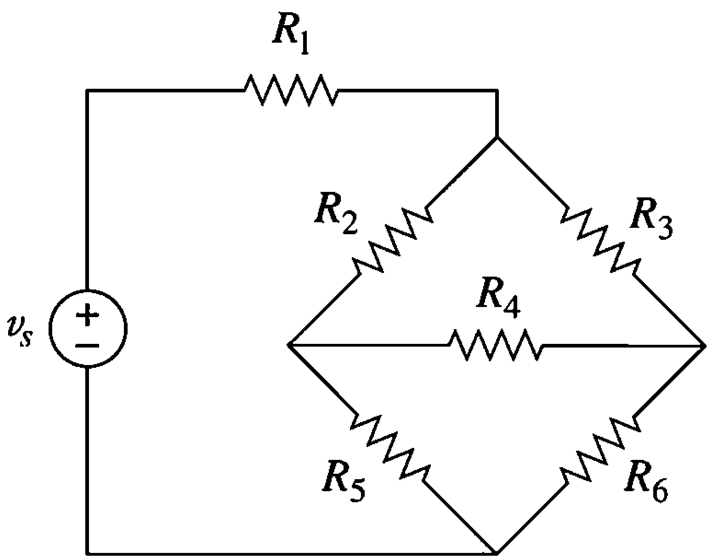
Wye-Delta Transformations

- There are cases where resistors are neither parallel nor series
- Consider the bridge circuit shown here
- This circuit can be simplified to a three-terminal equivalent



- The Y-Δ transform, also written wye-delta and also known by many other names, is a mathematical technique to simplify the analysis of an electrical network.
- The aim is to analyse the circuit when the resistors are neither in parallel nor in series.

Δ-TO-Y AND Y-TO-Δ

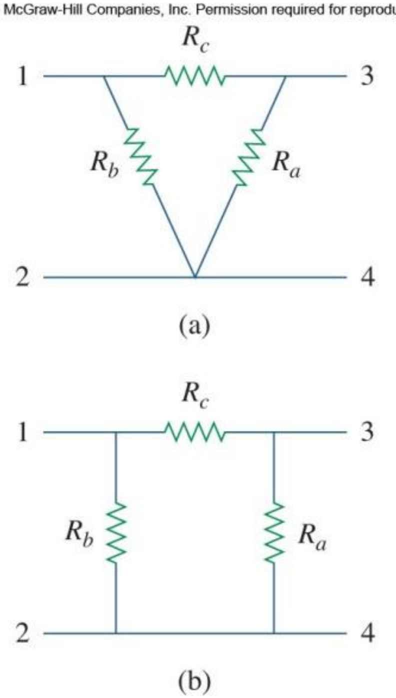


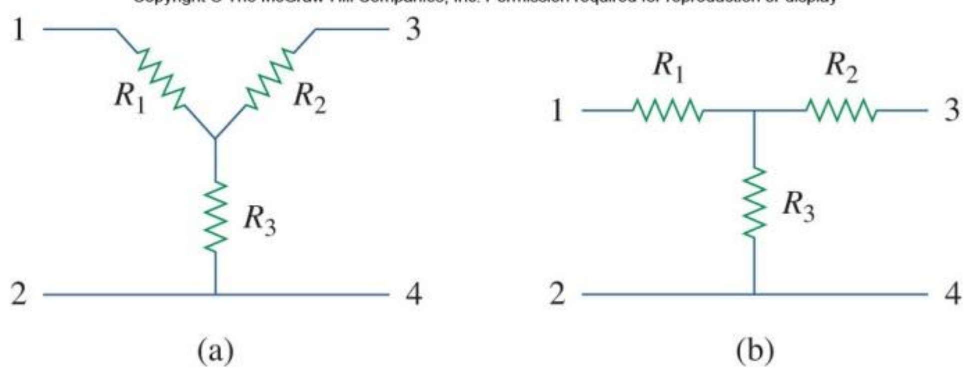
- Solution: Use three terminal equivalent networks:
  a) Wye (Y) or Tee (T)
  b) Delta (Δ) or Pi (π)

- Useful in:
  a) Three phase networks
  b) Electrical filters
  c) Matching networks

Wye-Delta Transformations II

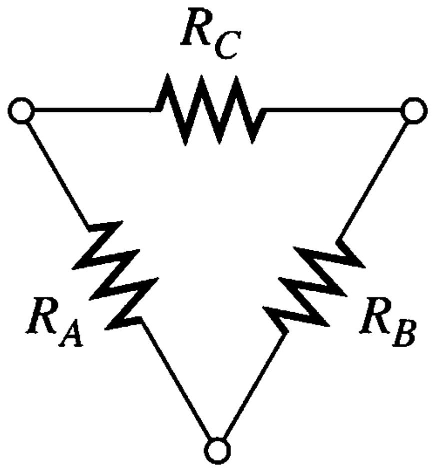
- Two topologies can be interchanged:
  - Wye (Y) or tee (T) networks
  - Delta (Δ) or pi (Π) networks
  - Transforming between these two topologies often makes the solution of a circuit easier



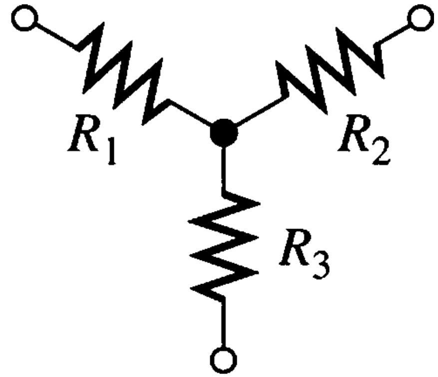


How to Apply Transformation?

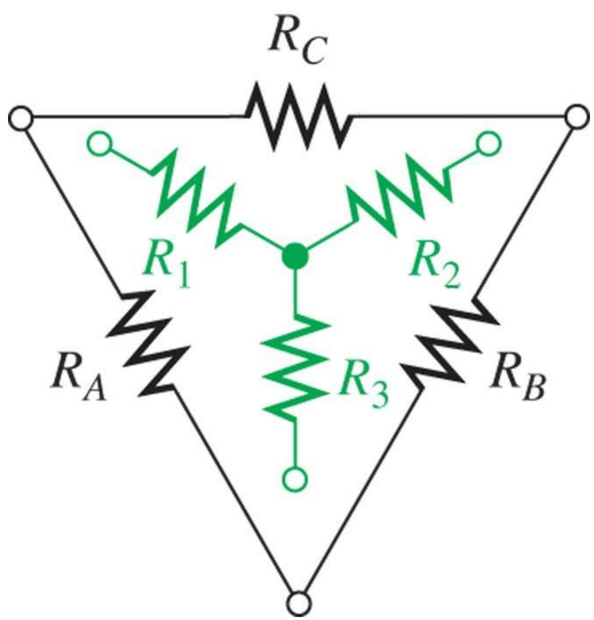
Delta (Δ)



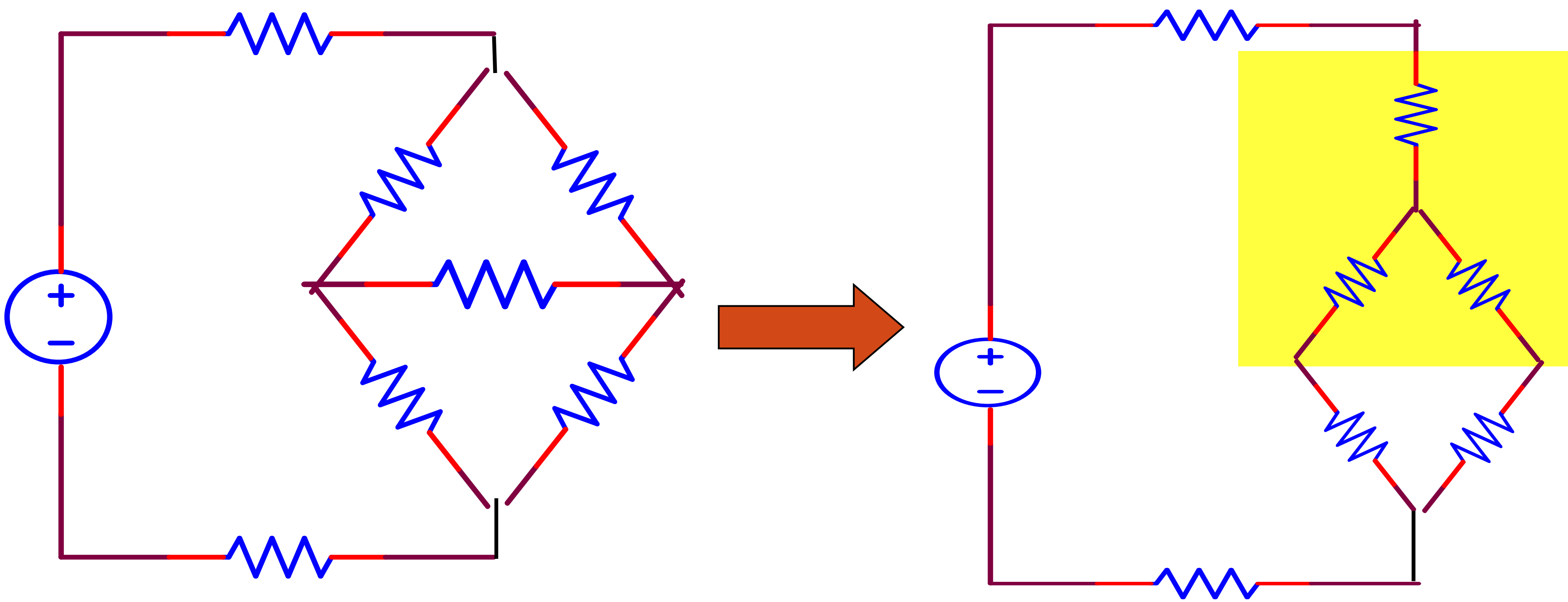
(a) Delta



Wye (Y)

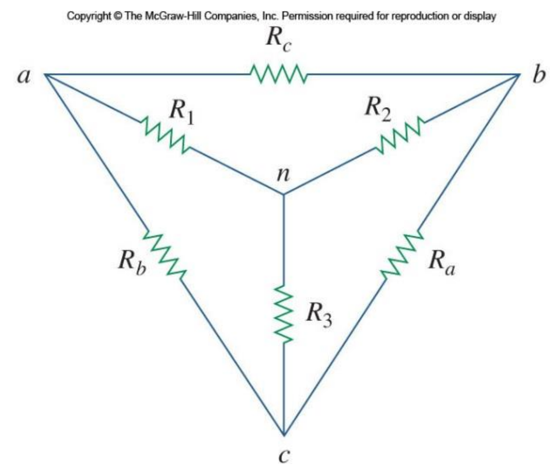


How to Apply Transformation?



Wye-Delta Transformations III

- The superimposed wye and delta circuits shown here will used for reference
- The delta consists of the outer resistors, labeled a,b, and c
- The wye network are the inside resistors, labeled 1,2, and 3



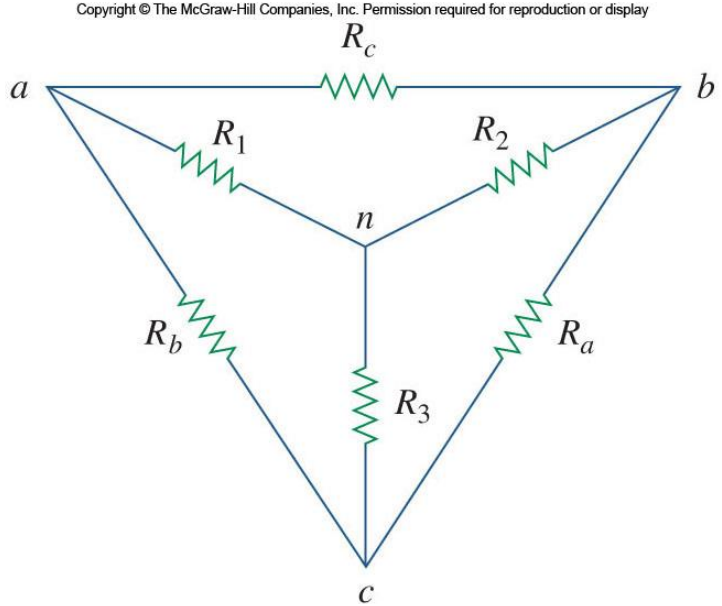
Delta to Wye

- The conversion formula for a delta to wye transformation are:

$$R_1 = \frac{R_b R_c}{R_a + R_b + R_c}$$

$$R_2 = \frac{R_c R_a}{R_a + R_b + R_c}$$

$$R_3 = \frac{R_a R_b}{R_a + R_b + R_c}$$



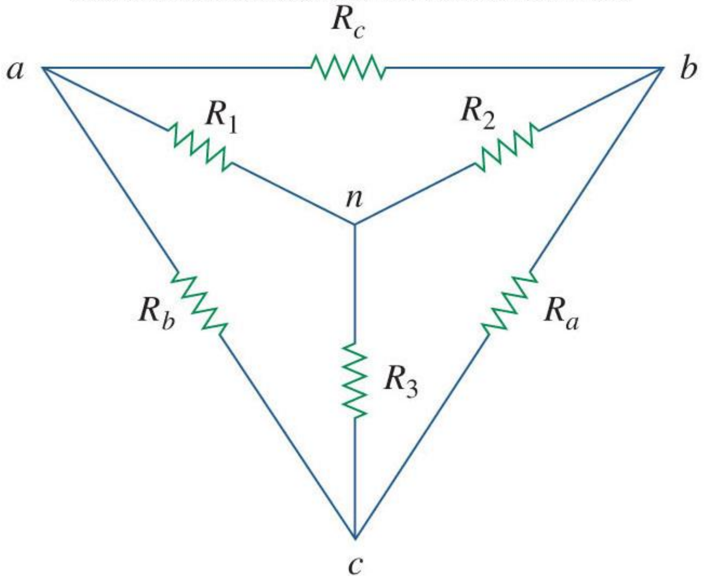
Wye to Delta

- The conversion formula for a wye to delta transformation are:

$$R_a = \frac{R_1R_2 + R_2R_3 + R_3R_1}{R_1}$$

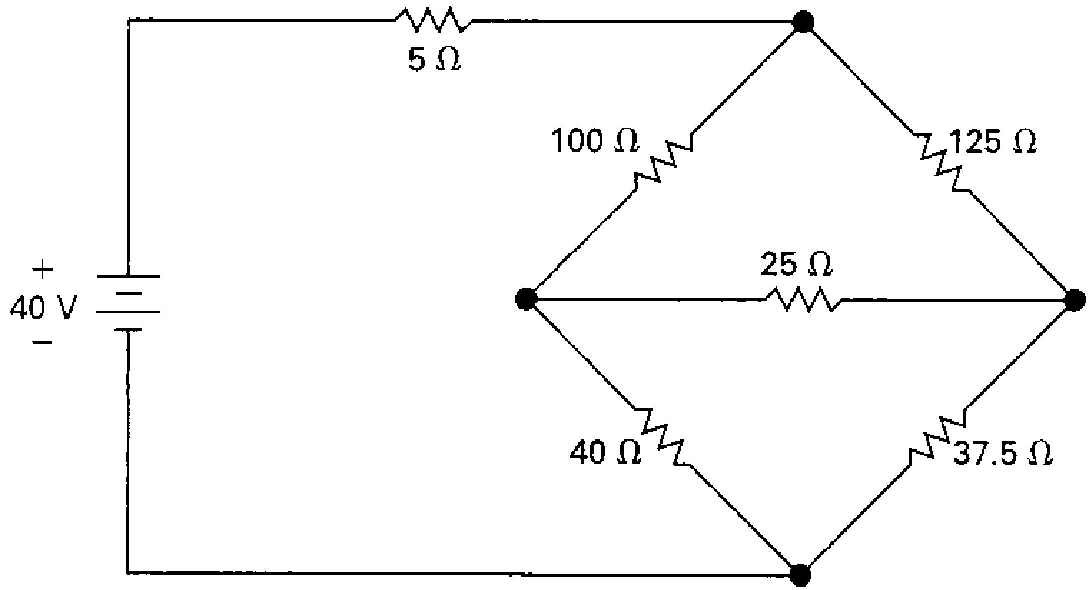
$$R_b = \frac{R_1R_2 + R_2R_3 + R_3R_1}{R_2}$$

$$R_c = \frac{R_1R_2 + R_2R_3 + R_3R_1}{R_3}$$



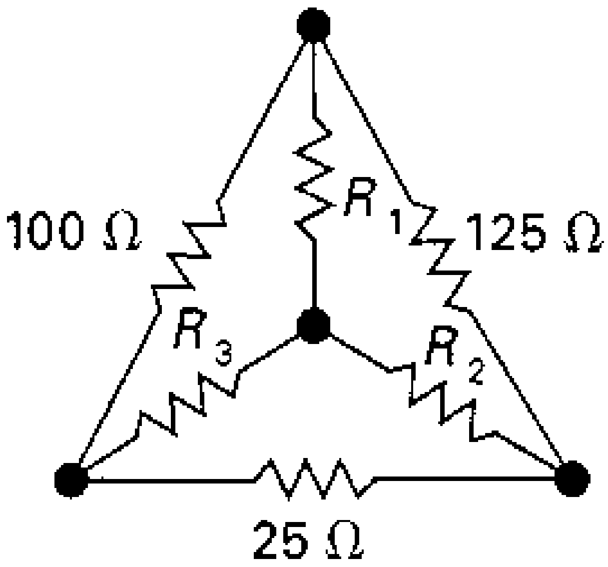
Δ-TO-Y AND Y-TO-Δ

Find the current and power supplied by the 40V sources in the circuit shown below.



- We can find this equivalent resistance easily after replacing either: upper Δ (100, 125, 25Ω) or lower Δ (40, 25, 37.5Ω) with its equivalent Y.
- We choose to replace the upper Δ.

Δ-TO-Y AND Y-TO-Δ



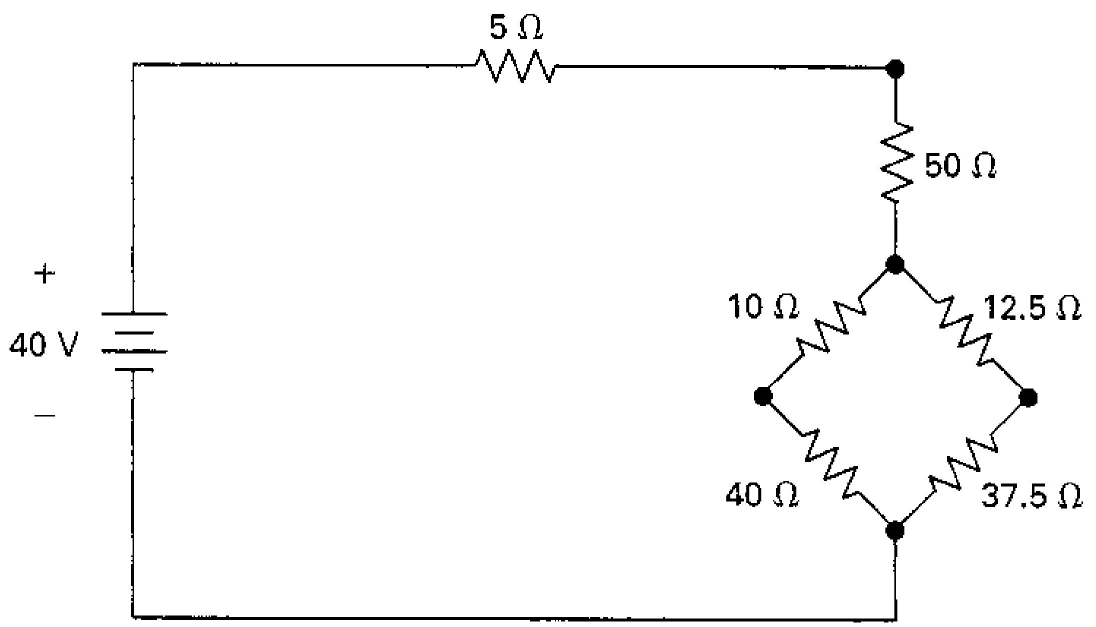
$$R_1 = \frac{(100)(125)}{100+125+25} = 50\Omega$$

$$R_2 = \frac{(125)(25)}{100+125+25} = 12.5\Omega$$

$$R_3 = \frac{(100)(25)}{100+125+25} = 10\Omega$$

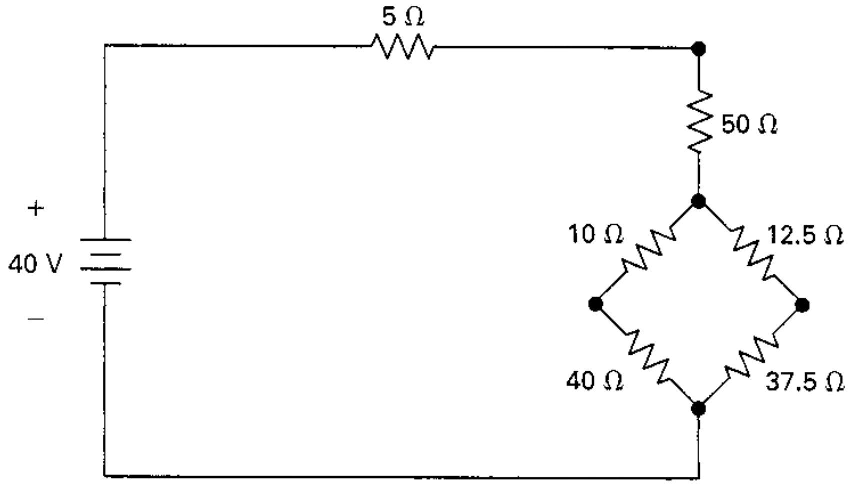
Δ-TO-Y AND Y-TO-Δ

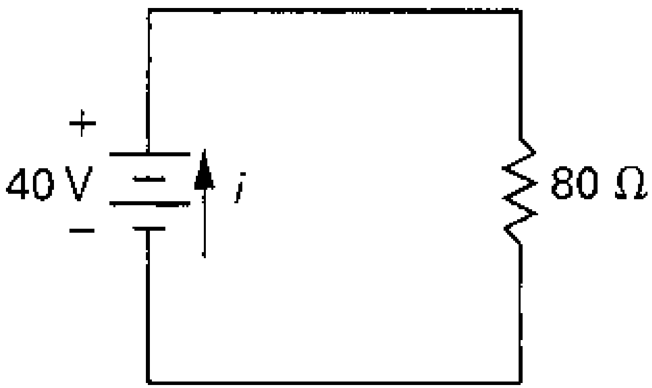
- Substituting the Y-resistor into the equivalent circuit:



Δ-TO-Y AND Y-TO-Δ

- Calculate the equivalent resistance:

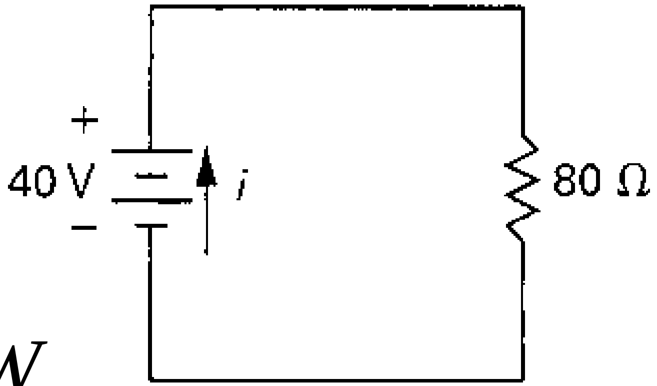




$$R_{eq} = 55 + \frac{(50)(50)}{(50+50)} = 80\Omega$$

- Then, the current and power values are:

$$I_T = \frac{V_T}{R_T} = \frac{40V}{80\Omega} = 0.5A$$



$$P = VI = (40V)(0.5A) = 20W$$

KVL – Kirchhoff's Voltage Law

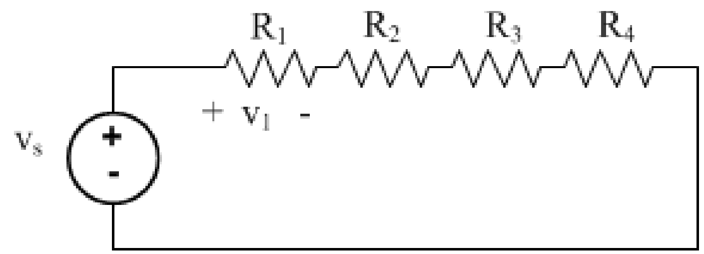
The sum of the voltage drops around a closed path is zero.

KCL – Kirchhoff's Current Law

The sum of the currents leaving a node is zero.

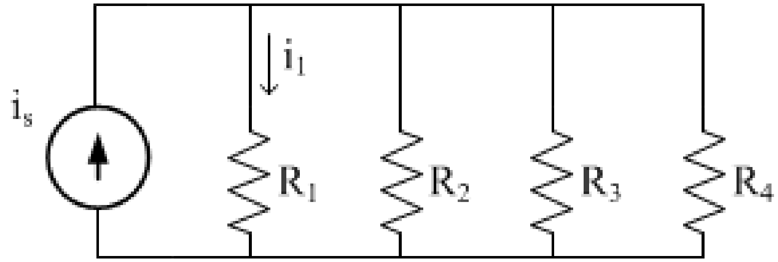
Voltage Divider

$$v_1 = \frac{R_1}{R_1 + R_2 + R_3 + R_4} v_s$$

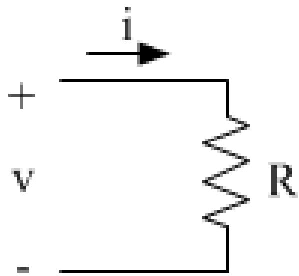


Current Divider

$$i_1 = \frac{\frac{1}{R_1}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}} i_s$$



Resistor



$$v = Ri$$

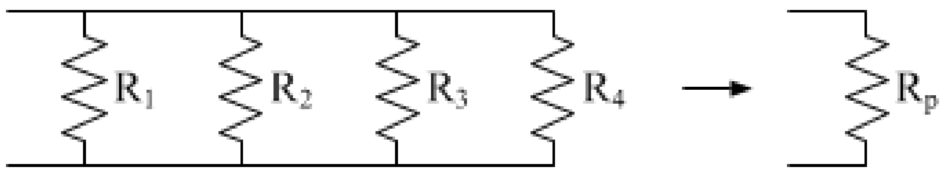
Power absorbed

$$p = vi = Ri^2 = \frac{v^2}{R}$$

Energy dissipated

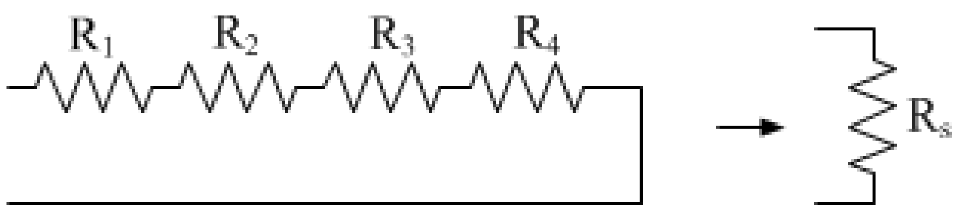
$$w = \int p\, dt = \int_{\text{one period}} p\, dt$$

Parallel Resistors



$$R_p = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}}$$

Series Resistors



$$R_s = R_1 + R_2 + R_3 + R_4$$

Review

	Series	Parallel
Resistance	$R_T = R_1 + R_2 + \cdots + R_n$	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots\ldots + \frac{1}{R_n}$ $R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \ldots\ldots + \frac{1}{R_n}}$ $R_T = R_1 \| R_2 \Rightarrow R_T = \frac{R_1 R_2}{R_1 + R_2}$
Current	$I_T = I_1 = I_2 = I_n$	$I_T = I_1 + I_2 + \cdots + I_n$
Voltage	$V_T = V_1 + V_2 + \cdots + V_n$	$V_T = V_1 = V_2 = V_n$

Review

	Series	Parallel
	KVL	KCL
Law	$V_T = V_1 + V_2 + V_3 \cdots + V_n$	$I_T = I_1 + I_2 ... + I_n$
	$V_T - V_1 - V_2 - V_3 - \cdots - V_n = 0$	$I_T - I_1 - I_2 - ... - I_n = 0$
	VDR	CDR
Rule	$V_x = \left(\frac{R_x}{R_T}\right) V_T$	$I_x = \left(\frac{R_T}{R_x}\right) I_T$

$$R_T = R_1 \| R_2 \Rightarrow$$

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

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