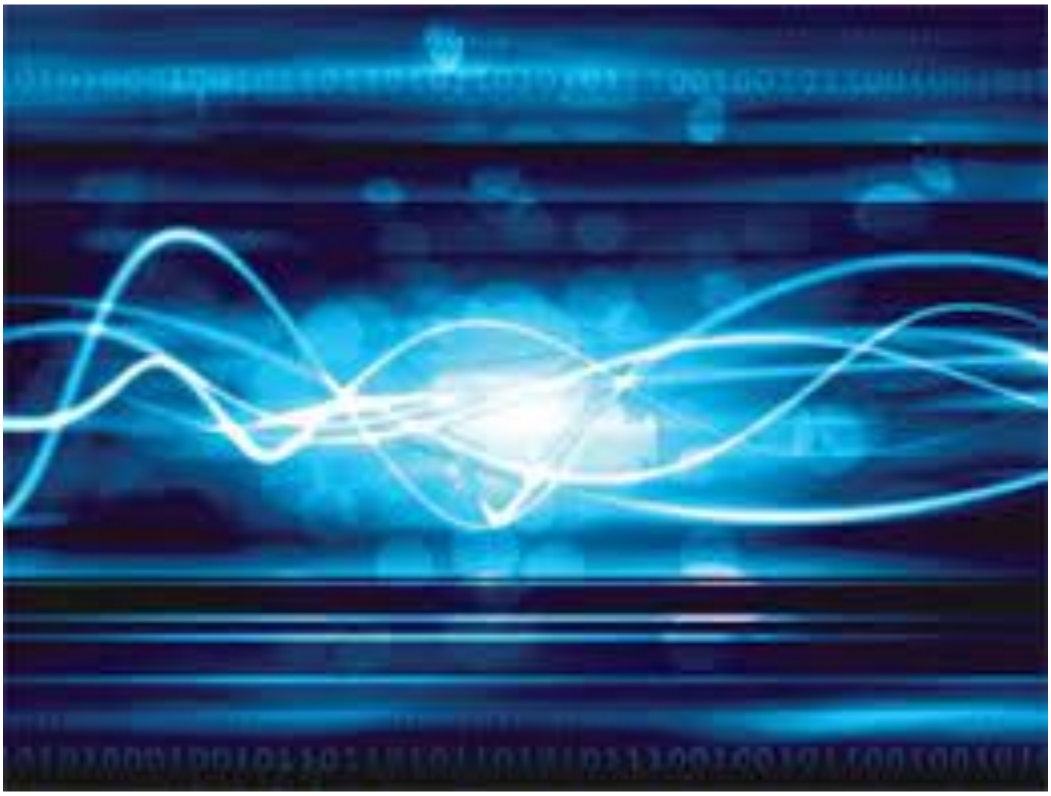
DC Theory

Underpinning Knowledge



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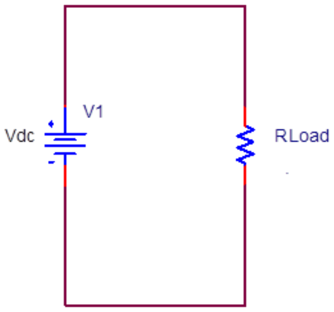
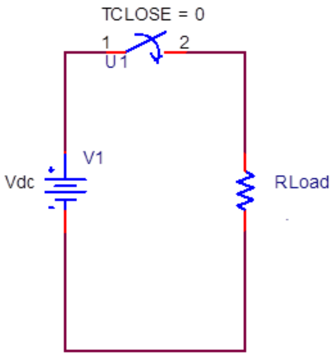
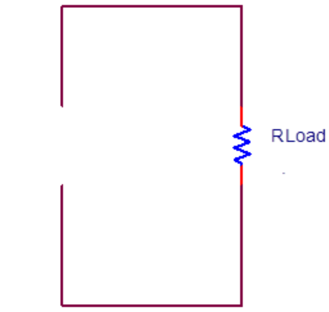
1 Be able to use circuit theory to determine voltage, current and resistance in direct current (DC) circuits

Voltage and Current
With the correct circuit condition, when Voltage is applied current will flow, where current is the flow of electrons. Let us consider the following circuits:

	Voltage and Current The circuits is closed and current flows.
	Voltage and No Current The circuits is open and due to the switch TCLOSE and no current flows.
	No Voltage and No Current As there Is no voltage source, no current will flow.

Now let us look at the various components of the above circuits.

Voltage (V) Unit: Volts

Voltage is a measure of the energy carried by the charge. It is normally generated by a battery or power supply. Ideally it should be called potential difference or p.d.

Current (I) Unit: Amperes

Current is the rate of flow of charge. It is not generated, but drawn from a supply. It is often stated as milliamps (10^{-3}).

1A (1 amp) is quite a large current for electronics, so mA (milliamps) are often used. m (milli) means "thousandth":

1mA = 0.001A, or 1000mA = 1A

Resistance (R) Unit: Ohm (Ω)

Resistance is the opposition of current flow in a circuit. As the voltage drives the current through the circuit, energy is used up and appears as heat in the resistor.

Resistance is measured in ohms and the symbol is the omega Ω.
1 Ω is small for electronics so resistances are often given in kΩ and MΩ.
1 k Ω = 1000 Ω   1 MΩ = 1000000 Ω.

Resistors can have resistances as low as 0.1 Ω or as high as 100 MΩ.

(See SI Prefixes)

Electromotive Force (EMF)

When a voltage is generated by a source, battery, power supply, solar cells. It has been traditionally called an "electromotive force" or emf where the emf represents energy per unit charge (voltage) which has been made available by the generating mechanism and is not a "force". The term emf is retained for historical reasons.

Potential difference (P.D)

The flow of electricity is attributed entirely to the potential difference. It is the difference in energy at two locations. If you consider a piece of wire, which is unconnected, at both ends, it has the same energy level; therefore, there will be no potential difference. As there is no p.d. there will be no current flow. If you change the value at one end, up or down there will be a potential difference, and the current will flow.

Potential difference can be defined as the amount of energy required to move a charge around a circuit. It is measured in Volts and commonly called as 'Voltage'.

Potential difference is almost similar to emf or electro motive force, difference being that emf is for the open circuits.

Conductors

A Conductor is materials, which easily allow the flow of electrons due to its low resistance. Outer electrons of the atoms are loosely bound and are free to move through the material.

Examples:

Metals-aluminium, copper, silver and carbon.

Insulators

An Insulator is materials which do not conduct electricity an insulator does not have any free electrons available for the carriage of current due to high resistance. This is because the valence band electrons of these materials are bound very tightly to their parent nuclei and require vast amounts of energy to break that bond. Non-metallic solids are said to be good insulators

Examples:

Most plastics such as polythene and PVC (polyvinyl chloride), paper, glass.

Resistivity

The electrical resistance of a wire would be expected to be higher for a longer wire and less for a wire with a large cross-sectional area. The electrical resistance would also depend on the material of which the wire is made. he resistance of a wire is expressed as:

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

ρ = resistivity
L = length
A = cross sectional area

The values of resistivity for a range of materials is shown in Appendix C.

Example

Calculate the resistance of 1,000m of 16mm^2 (CSA) single copper conductor. Take ρ to be 1.72 x 10^{-8} Ω/metre.

$$R = \rho \frac{l}{a}$$

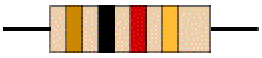
$$= 1.72 \times 10^{-8} \times \frac{1{,}000}{16 \times 10^{-6}}$$

$$= \mathbf{1.075\Omega}$$

See Appendix D for converting mm^2 to M^2

Now attempt worksheet: Resistivity

Resistors

Example:  Circuit symbol: 

Function

Resistors restrict the flow of electric current.

Resistor values - the resistor colour code

Resistance is measured in ohms; the symbol for ohm is an omega Ω.
1 $\Omega$is quite small so resistor values are often given in kΩ and MΩ.
1 kΩ = 1000 Ω 1 MΩ = 1000000 Ω.

Resistor values are normally shown using coloured bands where each band represents a number as shown below.

The Resistor Colour Code	
Colour	Number
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Grey	8
White	9

Most resistors have 4 bands:

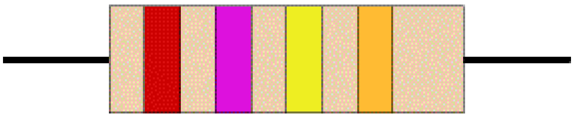
The **first band** gives the **first digit**.

The **second band** gives the **second digit**.

The **third band** indicates the **number of zeros**.

The fourth band shows the tolerance of the resistor.

Example



This resistor has red (2), violet (7), yellow (4 zeros) and gold bands.
So its value is 270000 Ω= 270 kΩ.

On circuit diagrams the Ω is usually omitted and the value is written 270K.

Resistor Tolerance (fourth band)

The tolerance of a resistor is normally shown by the fourth band of the colour code on the resistor.

silver ±10%, gold ±5%, red ±2%, brown ±1%.
If no fourth band is shown the tolerance is ±20%.

Resistor shorthand

Resistor values are often written on circuit diagrams using a code system which avoids using a decimal point because it is easy to miss the small dot. Instead the letters R, K and M are used in place of the decimal point. To read the code: replace the letter with a decimal point, then multiply the value by 1000 if the letter was K, or 1000000 if the letter was M. The letter R means multiply by 1.

For example:

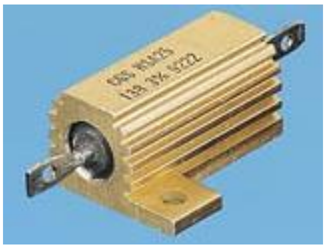
560R means 560 Ω
2K7 means 2.7 kΩ = 2700 Ω
39K means 39 kΩ
1M0 means 1.0 MΩ = 1000 kΩ

Now attempt worksheet: Resistors

Power Ratings of Resistors

Electrical energy is converted to heat when current flows through a resistor. Usually the effect is negligible, but if the resistance is low (or the voltage across the resistor high) a large current may pass making the resistor become noticeably warm. The resistor must be able to withstand the heating effect and resistors have power ratings to show this.

Power ratings of resistors are rarely quoted in parts lists because for most circuits the standard power ratings of 0.25W or 0.5W are suitable. When a higher power rating is required, these will be for very low resistor values or very high voltages.



High power resistors
(5W top, 25W bottom)

The power, P, developed in a resistor is given by:

$P = I^2 \times R$ where: P = power developed in the resistor in watts (W)

or I = current through the resistor in amps (A)

$P = V^2 / R$ R = resistance of the resistor in ohms (Ω)

V = voltage across the resistor in volts (V)

Examples:

A 470Ω resistor with 10V across it, needs a power rating $P = V^2/R = 10^2/470 = 0.21$W.
In this case a standard 0.25W resistor would be suitable.

A 27Ω resistor with 10V across it, needs a power rating $P = V^2/R = 10^2/27 = 3.7$W.
A high power resistor with a rating of 5W would be suitable

Resistor Types

Carbon Resistor - The most common type of resistor. They are used in low and medium power applications and are economical to make.

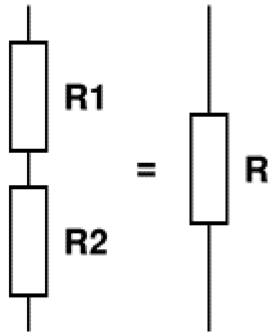
Film resistors - Made from metal film. They have very good temperature stability, lower noise. They are often used in circuits operating at higher frequencies.

Wire wound resistors- Used for very low values and normally can have very high power ratings.

Now attempt worksheet: Power Ratings of Resistors

Resistors connected in Series

When resistors are connected in series their combined resistance is equal to the individual resistances added together. For example if resistors R1 and R2 are connected in series their combined resistance, R, is given by:



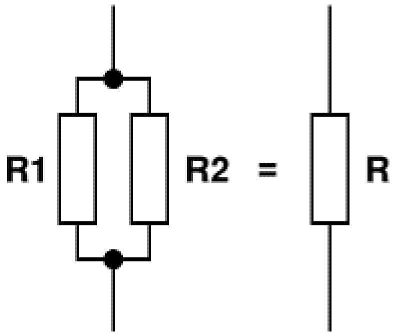
Combined resistance in series: $R = R1 + R2$

This can be extended for more resistors: $R = R1 + R2 + R3 + R4 + ...$

Note that the combined resistance in series will always be greater than any of the individual resistances.

Resistors connected in Parallel

When resistors are connected in parallel their combined resistance is less than any of the individual resistances. There is a special equation for the combined resistance of two resistors R1 and R2:



Combined resistance of two resistors in parallel: $R = \dfrac{R1 \times R2}{R1 + R2}$

For more than two resistors connected in parallel a more difficult equation must be used. This adds up the reciprocal ("one over") of each resistance to give the reciprocal of the combined resistance, R:

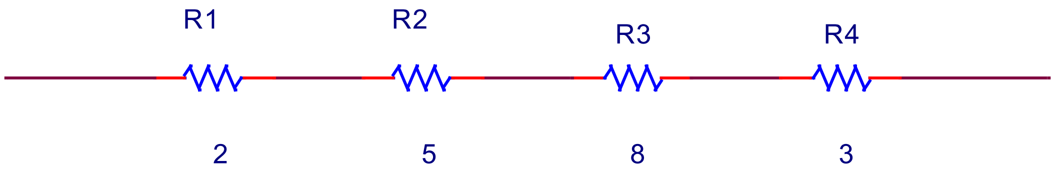
$$\frac{1}{R} = \frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3} + ...$$

The simpler equation for two resistors in parallel is much easier to use!

Note that the combined resistance in parallel will always be less than any of the individual resistances.

Example 1

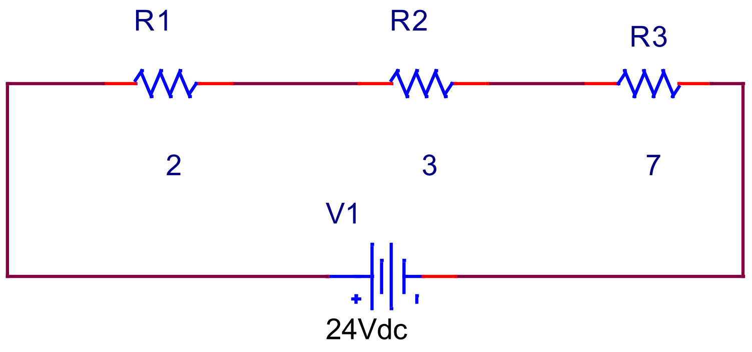
Calculate the total resistance of the circuit shown below:



$$
\begin{aligned}
R_t &= R_1 + R_2 + R_3 + R_4 \\
&= 2 + 5 + 8 + 3 \\
&= \mathbf{18\Omega}
\end{aligned}
$$

Example 2

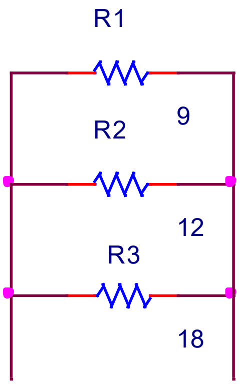
Calculate the total circuit resistance in the circuit shown below:



$$
\begin{aligned}
R_t &= R_1 + R_2 + R_3 \\
&= 2 + 3 + 7 \\
&= \mathbf{12\Omega}
\end{aligned}
$$

Example 3

Calculate the total resistance of a parallel circuit if:
$R_1 = 9\Omega,\ R_2 = 12\Omega$ and $R_3 = 18\Omega$.



$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$= \frac{1}{9} + \frac{1}{12} + \frac{1}{18}$$

Find the lowest common denominator, which is 36:

$$\frac{1}{R_t} = \frac{4 + 3 + 2}{36}$$

$$\frac{1}{R_t} = \frac{9}{36}$$

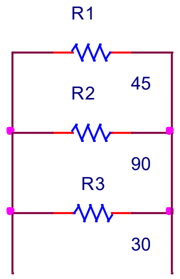
Inverting both sides of the equation will give us R_t:

$$R_t = \frac{36}{9}$$

$$\mathbf{4\Omega}$$

The total resistance of the circuit will determine the amount of current that will flow in that circuit.

Example 4
Calculate the total resistance of a parallel circuit if $R_1 = 45\Omega$,
$R_2 = 90\Omega$ and $R_3 = 30\Omega$



$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$= \frac{1}{45} + \frac{1}{90} + \frac{1}{30}$$

Find the lowest common denominator, which is 90:

$$\frac{1}{R_t} = \frac{2 + 1 + 3}{90}$$

$$\frac{1}{R_t} = \frac{6}{90}$$

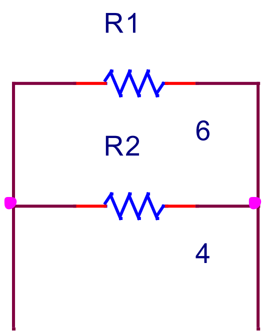
Inverting both sides of the equation will give us R_t:

$$R_t = \frac{90}{6}$$

$$\mathbf{15\Omega}$$

It can be seen that in all parallel circuits the total resistance of the circuit is **always less than** the smallest resistance in that circuit.

Two resistors in parallel



When there are only two resistors in parallel, the equivalent total resistance of the combination may be found by using the **product over sum** method, as shown below.

- The **product** of two numbers is the **multiplication** of the two numbers.
- The **sum** of two numbers is the **addition** of the two numbers.

Example 5
Calculate the total resistance of two resistors connected in parallel if $R_1 = 6\Omega$ and $R_2 = 4\Omega$.

$$
\begin{aligned}
R_t &= \frac{R_1 \times R_2}{R_1 + R_2} \\
&= \frac{6 \times 4}{6 + 4} \\
&= \frac{24}{10} \\
&\mathbf{2.4\Omega}
\end{aligned}
$$

This method only works for two resistors in parallel.

If all the resistors in parallel are of the same value, then all that has to be done, in order to calculate the total resistance of the circuit, is to take any one resistor and divide its value by the number of resistors that are in the parallel combination.

Now attempt worksheet: Resistors in Series and Parallel

Ohm's Law

Ohms law states that the electric current flowing through a component is proportional to the voltage applied. The ratio of voltage to current is called the resistance.

The current can be calculated from the equation:

Ohm's Law

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

Electric current = Voltage / Resistance

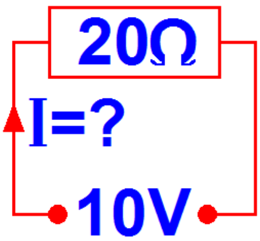
Task:

Re arrange Ohms law to get an equation for V and R

power and energy formulae - $V = IR$, $P = IV$, $W = Pt$

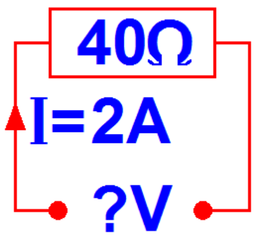
Example 1
An EMF of 10 volts is applied to a resistance of 20Ω. Calculate the current that will flow.

$$\begin{aligned} \mathbf{I} &= \frac{\mathbf{V}}{\mathbf{R}} \\ &= \frac{\mathbf{10}}{\mathbf{20}} \\ &= \mathbf{0.5A} \end{aligned}$$



Example 2
Calculate the applied EMF when 2 amperes flows through a resistance of 40Ω.

$$\begin{aligned} \mathrm{V} &= \mathrm{I} \times \mathrm{R} \\ &= 2 \times 40 \\ &= \mathbf{80\ volts} \end{aligned}$$

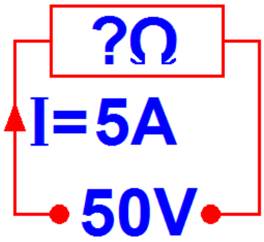


Example 3
When an EMF of 50 volts is applied to a circuit, a current of 5 amperes flows. Calculate the resistance of the circuit.

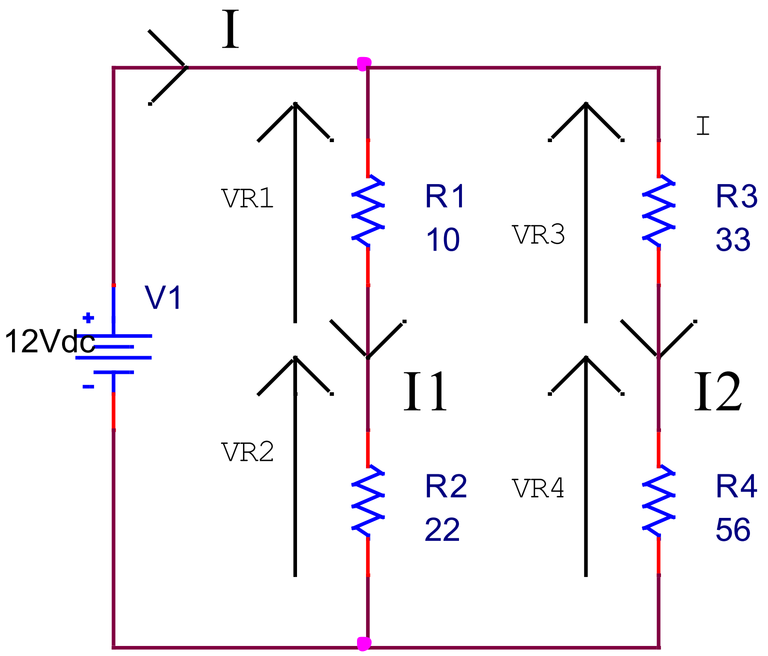
$$R = \frac{V}{I}$$

$$= \frac{50}{5}$$

$$= \mathbf{10}\ \Omega$$



Example 4
Consider the following circuit



$$\frac{1}{R_{TOTAL}\ ,\ R_T} = \frac{1}{R1 + R2} + \frac{1}{R3 + R4}$$

$$\frac{1}{R_{TOTAL}\ ,\ R_T} = \text{Ans}$$

R_{TOTAL} = 1 / Ans

$$I = \frac{V_{Supply}}{R_{TOTAL}}$$

$$I1 = \frac{V_{Supply}}{R1 + R2}$$

$$I2 = \frac{V_{Supply}}{R3 + R4}$$

$V_{R1} = I_1 R_1$

$V_{R2} = I_1 R_2$

$V_{R3} = I_2 R_3$

$V_{R4} = I_2 R_4$

$$\frac{1}{R_{TOTAL}}, R_T = \frac{1}{10 + 22} + \frac{1}{33 + 56}$$

$$\frac{1}{R_{TOTAL}}, R_T = 0.415$$

$R_{TOTAL} = 1 / 0.415 = 24.07\Omega$

$$I = \frac{12}{24.07} = 0.499A$$

$$I1 = \frac{12}{32} = 0.375A$$

$$I2 = \frac{12}{89} = 0.135A$$

$V_{R1} = I_1 R_1 = 3.75v$

$V_{R2} = I_1 R_2 = 8.25v$

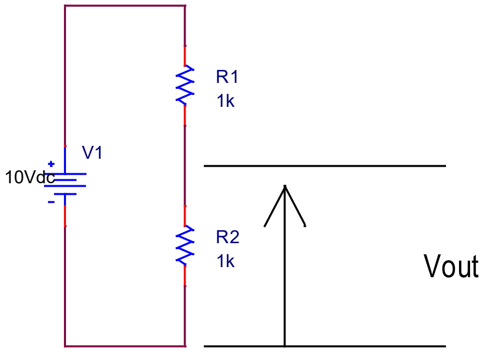
$V_{R3} = I_2 R_3 = 4.455v$

$V_{R4} = I_2 R_4 = 7.56v$

Now attempt worksheet: Ohms Law

Potential dividers

A Potential divider circuit consists of two resistors (or more) which divide up the voltage within the circuit. This ensures that a part of the circuit only receive the voltage required.

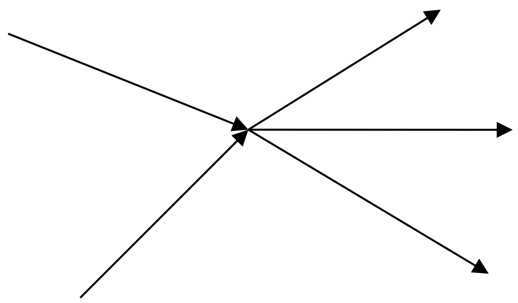


Now attempt worksheet: Ohms Law

Kirchhoff's First law

In any network, the sum of the current flowing through a point is equal to the sum of the current flowing from that point or the algebraic sum of that point is equal to zero.

Consider the following:



$$I1 + I4 = I2 + I3 + I5$$

or

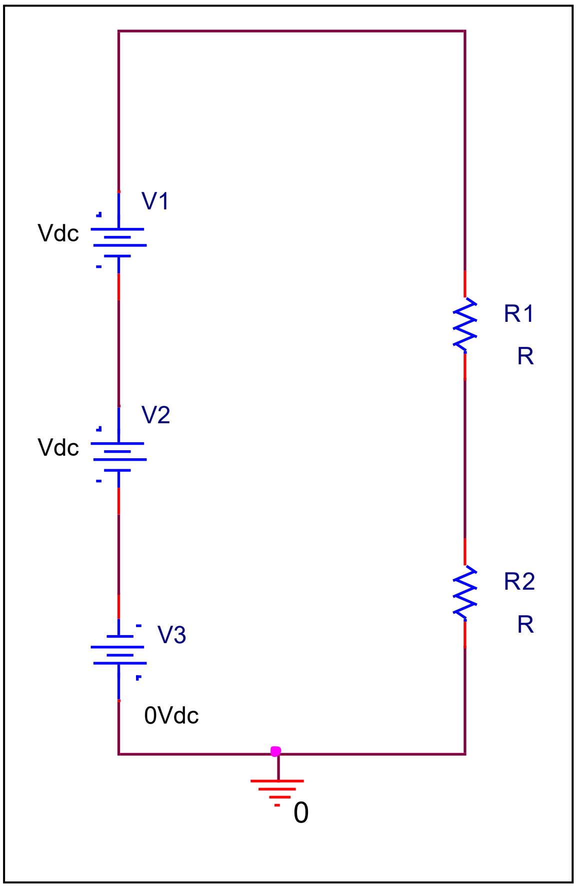
$$I1 + I4 - I2 - I3 - I5 = 0$$

Example

Kirchhoff's Second law

In any closed path in a network the algebraic sum of the emf is equal to the algebraic sum of the potential differences (or product of current and resistance for each point of the closed path).

Consider the following:



For the current to flow in the direction shown, V1 + V2 must be greater than V3.

V1 + V2 – V3 = V4 + V5 where V4 is the voltage across R4 and V5 is the voltage across R5

Using Ohms law we get

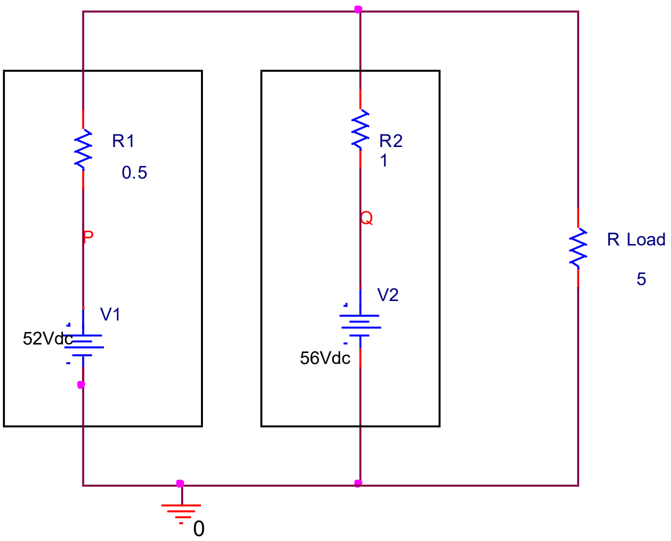
V1 + V2 – V3 = I R1 + I R2

Example

Two batteries P and Q are connected in parallel, +ve to +ve across a common 5 ohm load resistor. Battery P has an emf of 52v and internal resistance of 0.5 ohms. Battery Q has an emf of 56v and internal resistance of 1 ohm.

Find the magnitude and the direction of the current flowing in each part of the circuit and the power dissipated by the load resistor.

Circuit



Assume that the current flows leaving the positive terminals of the Batteries.

In the outer circuit

$V1 = V_{R1} + V_{RLoad}$

52 v = 0.5 I1 + 5 (I1 + I2)

52 v = 5.5 I1 + 5 I2 …………………………………………………… 1

In the inner circuit

$V2 = V_{R2} + V_{RLoad}$

56 v = 1 I2 + 5 (I1 + I2)

56 v = 5 I1 + 6 I2)……………………………………………………… 2

Multiply equation 1 by 6

33 I1 + 30 I2 = 312 ……………………………………………………..3

Multiply equation 2 by 5

25 I1 + 30 I2 = 280 ………………………………………………4

Equation 1 – 2

8 I1 = 32

Therefore I1 = +4A

Substitute I1 (4A) into equation 2

20 + 6 I2 =56

I2 = +6A

Battery P is discharging at 4 Amperes

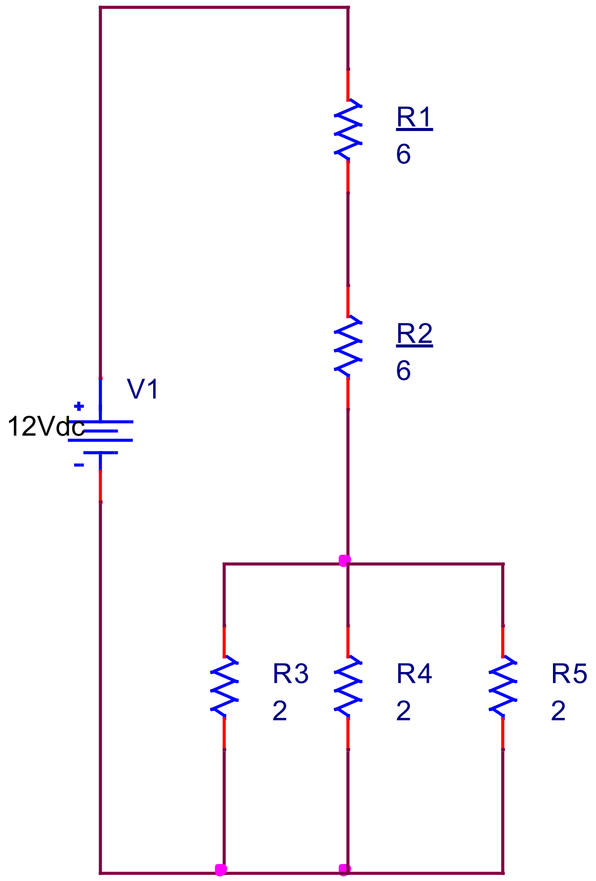
Battery Q is discharging at 4 Amperes

Current tin the load is (I1 + I2) = 4 + 6 = 10A

Now attempt worksheet: Kirchhoff's Laws

DC Networks

Networks with one DC power source and at least five components -two series resistor and three parallel resistors connected in a series parallel arrangement



When doing calculation in DC networks it is often required to complete mini equivalent circuits. In the diagram above, R1 and R2 could be considered as one resistor (R1 + R2, R3,4,5 could be considered as one resistor. Depending of what calculation is required will determine what value is used.

Now attempt worksheet: DC Networks

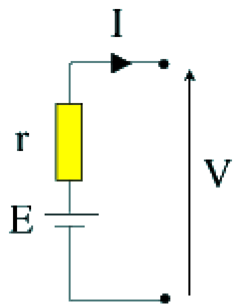
Internal resistance of a DC source

In theory, the voltage source is often considered a perfect device. This device provides a constant voltage independent on how much current is drawn. In practice, this is not the case.

If the current drawn from the power source increases, the voltage decreases.

All power supplies get warm during use, which illustrates that some of the energy that they provide is being converted to heat inside the power supply itself.

The power source can therefore be modelled as thus:



The emf of a power source has an internal resistance. When current is being supplied to a circuit the current flows through the internal resistance producing an internal voltage drop (Ohms law). This internal voltage drop reduces the voltage across the power supply terminals. The power dissipated by the internal resistance represents the heat generated by the power supply.

The terminal voltage (V) is equal to the e.m.f. voltage (E) minus the internal voltage drop (Ir)
(using ohms law :- internal voltage drop = current (I) x internal resistance (r))

$V = E - Ir$

To model any real power supply, we just have to determine the correct values of E and r to use.

From the above equation we can see that when the power supply is not connected to a circuit there will be no current flowing therefore:

$V = E - 0 \times r$

$V = E$

i.e. the emf voltage is equal to the open circuit terminal voltage of the power supply.

The internal resistance can be determined by connecting a circuit of known resistance and measuring the current that flows

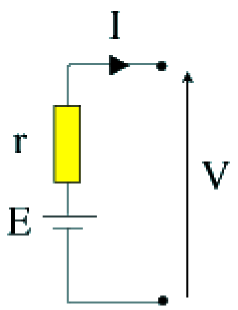
$I = E/(R + r)$

Therefore, $r = (E/I) - R$

The power supplied by the e.m.f. is given by $P = EI$ and the power dissipated in the power supply is given by $P = I^2r$
The energy provided by the e.m.f. is given by $W = EIt$ and the energy dissipated in the power supply is given by $W = I^2rt$

Example

Consider the following circuit:



If E = 12v and the internal resistance, r =0.5Ω . If a 5Ω resistor is connected to the circuit, calculate I and V.

$I = E/(R + r)$

$I = 12/(5 + 0.5) = 5.5A$

$Vr=Ir = 5.5A \times 0.5 = 2.75v$

Therefore $V = E-Vr = V =12 – 2.75 = 9.25v$

Now attempt worksheet: Internal resistance of a DC source

Temperature coefficient - Resistance Temperature coefficient
The electrical resistance of a conductor increases with temperature and the resistance is proportional to the temperature change.

The equation is thus:

$$\frac{\Delta R}{R_0} = \alpha \Delta T \qquad \alpha = \text{temperature coefficient of resistance.}$$

Alternatively, expressed in terms of the resistance at some standard temperature from a reference table:

$$\frac{R - R_0}{R_0} = \alpha(T - T_0) \quad \text{or} \quad R = R_0[1 + \alpha(T - T_0)]$$

Example

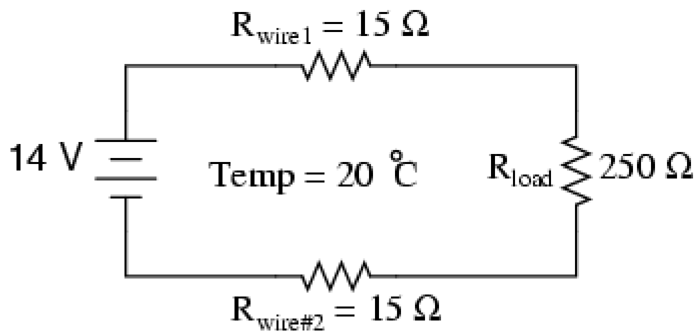
The resistance of a length of copper in an electronic circuit is 18 Ω. If the circuit operates at 50^0. What is the new value of resistance for the wire?

$$R = R_{ref}\,[1 + \alpha\,(T - T_{ref})]$$

$$R = 18\,[1 + 0.004041\,(50^0 - 20^0)]$$

$$R = 20.18214\Omega$$

Consider the following circuit to see how temperature can affect wire resistance, and the circuit performance:



This circuit has a total wire resistance (wire 1 + wire 2) of 30Ω at standard temperature. Setting up a table of voltage, current, and resistance values we get:

	$Wire_1$	$Wire_2$	Load	Total	
E	0.75	0.75	12.5	14	Volts
I	50 m	50 m	50 m	50 m	Amps
R	15	15	250	280	Ohms

At 20° Celsius, we get 12.5 volts across the load and a total of 1.5 volts (0.75 + 0.75) dropped across the wire resistance. If the temperature were to rise to 35° Celsius, we could easily determine the change of resistance for each piece of wire. Assuming the use of copper wire (α = 0.004041) we get:

$$R = R_{ref}\,[1 + \alpha(T - T_{ref})]$$

$$R = (15\ \Omega)[1 + 0.004041(35^{\circ} - 20^{\circ})]$$

$$R = 15.909\ \Omega$$

Recalculating our circuit values, we see what changes this increase in temperature will bring:

	$Wire_1$	$Wire_2$	Load	Total	
E	0.79	0.79	12.42	14	Volts
I	49.677m	49.677m	49.677m	49.677m	Amps
R	15.909	15.909	250	281.82	Ohms

As you can see, voltage across the load went down (from 12.5 volts to 12.42 volts) and voltage drop across the wires went up (from 0.75 volts to 0.79 volts) as a result of the temperature increasing. Though the changes may seem small, they can be significant for power lines stretching miles between power plants and substations, substations and loads. In fact, power utility companies often have to take line resistance changes resulting from seasonal temperature variations into account when calculating allowable system loading.

Now attempt worksheet: Resistance Temperature Coefficient

Appendix A

SI Prefixes

In engineering there are certain prefixes that are required and you must be able to change numbers from one prefix to another. The values can range from very large to very small.

The standard prefixes used in electronic engineering are:

Factor	Name	Symbol
10^{12}	Tera	T
10^{9}	Giga	G
10^{6}	Mega	M
10^{3}	Kilo	K
10^{-3}	milli	m
10^{-6}	micro	µ
10^{-9}	nano	n
10^{-12}	pico	p

Example

(i)1.45 mA = 0.00145A

(ii) 12pF = 120 nF

Task: Worksheet SI Prefix 1

Appendix B

Electrical Units
In electronic or electrical circuits, the range of components and units is varied and must be remembered by the engineer. The table below shows some of the standard electrical units and component values.

Standard Electrical Units

SI Unit	**Measure of**	**Symbol**	**Abbreviation**
Ampere	Electric Current	I	A
Volt	Electric potential/Potential difference/Electromotive force	V	V
Ohm	Electrical resistance	R	Ω
Rho	Resistivity	P	Ohm/m^3
Ohm	Impedance	Z	Ω
Henry	Inductance	L	H
Farad	Capacitance	C	F
Degrees Celsius	Celsius temperature	t	°C
Kilogram	Mass	m	kg
Newton	Force	F	N
Weber	Magnetic flux	Φ	Wb
Tesla	Magnetic flux density	B	T or Wb/m^2
Period	Duration of one cycle	p	s
Hertz	Frequency – number of cycles per second	f	Hz
Watts	Power	P	W
Joule	Energy/Work/Quantity of heat	E	J
Second	Time	t	s
Metre	Length	l	m
Square metre	Area	a	m^2
Coulomb	Charge	C	Q

Appendix C

Resistivity

Material	Resistivity at 20°C
Copper	1.72×10^{-8} ohm/metre^3
Aluminium	2.65×10^{-8} ohm/metre^3
Silver	1.59×10^{-8} ohm/metre^3
Gold	2.24×10^{-8} ohm/metre^3
Brass (58% copper)	5.90×10^{-8} ohm/metre^3
Brass (63% copper)	7.10×10^{-8} ohm/metre^3

Appendix D

Converting mm^2 to M^2

Cable CSA is usually quoted in mm^2 and this will need to be converted to M^2. In order to convert:

$$\mathrm{mm}^2 \text{ to } \mathrm{M}^2 \text{ multiply by } 10^{-6}$$

Appendix E

Temperature coefficients of resistance

TEMPERATURE COEFFICIENTS OF RESISTANCE, AT 20 DEGREES C

Material	Element/Alloy	"alpha" per degree Celsius
Nickel --------	Element ---------------	0.005866
Iron ----------	Element ---------------	0.005671
Molybdenum ----	Element ---------------	0.004579
Tungsten ------	Element ---------------	0.004403
Aluminum ------	Element ---------------	0.004308
Copper --------	Element ---------------	0.004041
Silver --------	Element ---------------	0.003819
Platinum ------	Element ---------------	0.003729
Gold ----------	Element ---------------	0.003715
Zinc ----------	Element ---------------	0.003847
Steel* ---------	Alloy -------------------	0.003
Nichrome -------	Alloy -------------------	0.00017
Nichrome V -----	Alloy -------------------	0.00013
Manganin -------	Alloy -------------------	+/- 0.000015
Constantan -----	Alloy -------------------	-0.000074

* = Steel alloy at 99.5 percent iron, 0.5 percent carbon