Unit V – Electricity & Magnetism pt I - Electricity

Topics covered:

- Law of Electrostatics
- Current, Electric Potential Difference (Voltage)
- Circuits (V&I only)
- Resistance
- Ohm's Law
- Equivalent Resistance
- Solving Circuits
- Electrical Power

Law of Electrostatics, Conductors, Insulators

Law of Electrostatics - Like charges repel, unlike charges attract.
Conductors – Materials that allow electrons to move within them easily.
Insulators - Materials that do not allow electrons to move within them easily.

Current, Potential Difference (Voltage)

Current (I) – the rate of flow of charges

$I = Q/t$ units: A – amps or amperes
1 A = 1 C/s

n.b. "Charges" can mean either moving negative charges, positive charges, or both in opposite directions. *Electron Flow* is a term used to describe moving (negatively charged) electrons, where *Conventional Current* refers to positive charges moving. For our purposes only, the term *current* will serve as a synonym for electron flow.

Charge (Q) – the charge due to the total amount of excess or missing electrons

$Q=Ne$ units: C - coulombs
N = number of excess/missing electrons
e = charge per electron = 1.602×10^{-19} C

How many electrons are there in 1 C of charge?

$$Q = Ne$$

$$N = \frac{Q}{e} = \frac{1C}{1.602\times10^{-19}C/electron} = 6.24 \times 10^{18} electrons$$

Voltage (V) – the comparison of the total amount of electrical potential energy that each charge has at one position relative to another position

V = ΔE/Q

Alternate definition – the amount of work required to move a positive charge from one position to another

V = W/Q units: V – volts

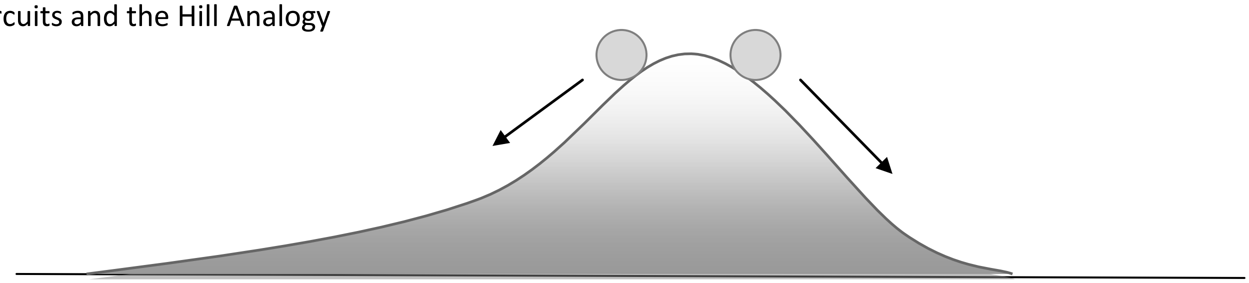
1 V = 1 J/C

<u>Circuits (V&I only)</u>

The Battery

A battery is, if oversimplifying, a chemical reaction waiting to happen. And once it does (by connecting its two ends with a conductor), chemical potential energy is converted into electrical energy: electrons at the negative terminal get lots of energy. It is much like rolling balls down a hill:

Circuits and the Hill Analogy



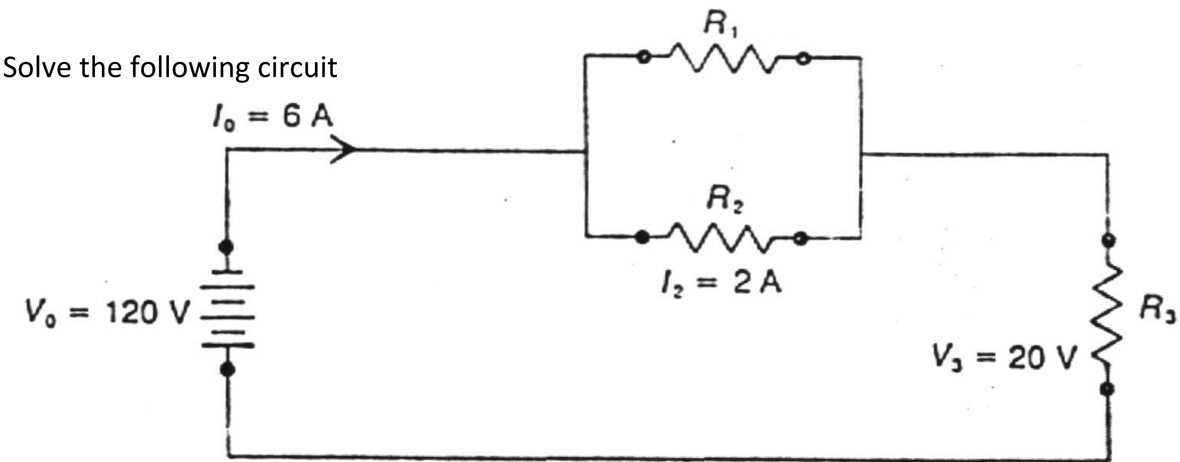
Balls at the top of a hill have gravitational potential energy, and when they roll down, that energy gets converted into other forms (e.g. kinetic energy, thermal energy, etc). It doesn't matter how the ball gets down to the ground, but when it does, it has lost all of its gravitational potential energy. To return a ball to the top of the hill to regain its gravitational potential energy, an external source of energy would be required.

In a circuit, the balls are like electrons, and the external source of energy is the battery. No matter what path electrons take towards the positive terminal, they will lose all their electrical energy along the way. And just as balls can only roll downwards (i.e. towards the ground), electrons can only in ways that take it to the positive terminal.

To Keep in Mind When Solving Circuits:

- Each electron leaving the battery gets the same amount of electrical energy (voltage)
- Each electron must lose all of its electrical energy before entering the positive terminal
- Electrons lose energy through loads only (not through wires)
- Electrons "want" to get back to the battery at every opportunity

e.g. Solve the following circuit



Current:

Since 6 A of current (electrons) leave the battery and 2 A go through R_2, that leaves 4 A to go through R_1.

Since all 6 A of current meet up again after the parallel paths of R_1 and R_2, all 6 A pass through R_3 as well.

Voltage:

Since each electron gets 120 V of energy from the battery, and each of them pass through R_3, they will each lose 20 V through R_3.

That leaves 100 V to lose for those electrons that went through R_1, and also 100 V lost for those that went through R_2.

	Voltage (Potential Difference)	**Current**
Battery	+120 V	6 A
Loads:		
R_1	-100 V	4 A
R_2	-100 V	2 A
R_3	-20 V	6 A

Resistance (R)

Resistance to electron flow is caused by
a) disorder in the atomic structure
b) impurities in the material
c) thermal vibrations of the particles of the load

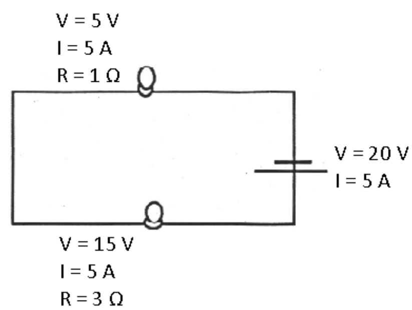
units: Ω – Ohms

Ohm's Law

The difference in potential energy across any load in a circuit (voltage) is the product of the amount of electrons passing through it (current) and the resistance of the load on those electrons:

$$V = IR$$

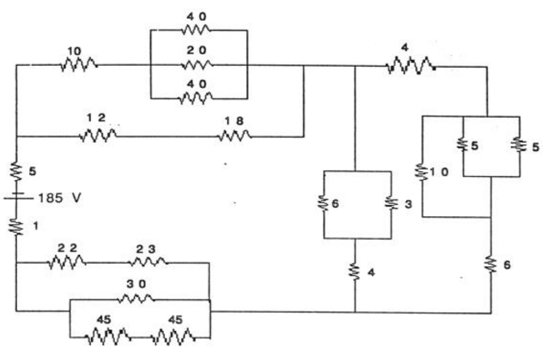
In the completed circuit on the right, each component obeys Ohm's Law



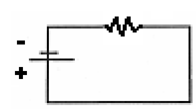
Equivalent Resistance

Each resistor in a circuit impedes the flow of charges a little bit. We can add all of these little bits to find out the TOTAL resistance of a circuit, which will be very useful.

It can turn a circuit like this:



Into this:

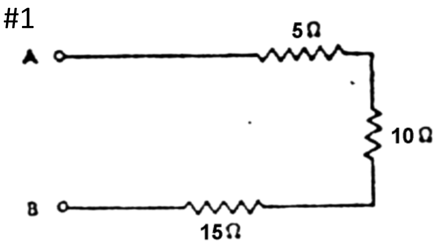


How? By adding up individual resistances and replacing them with equivalent resistances, step by step, until the total resistance of the circuit is determined.

Recall: Resistors in series are added like this: $R_{eq} = R_1 + R_2 + R_3 + \ldots$

Resistors in parallel are added like this: $\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$

e.g. #1



$R_1 = 5\ \Omega$

$R_2 = 10\ \Omega$

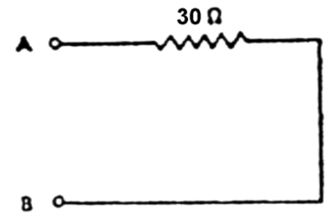
$R_3 = 15\ \Omega$

▶ $R_{eq} = R_1 + R_2 + R_3 + \ldots$

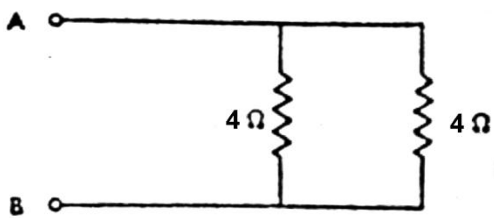
$= 5\ \Omega + 10\ \Omega + 15\ \Omega$

$= 30\ \Omega$

Redrawn:



e.g. #2



$R_1 = 4\ \Omega$

$R_2 = 4\ \Omega$

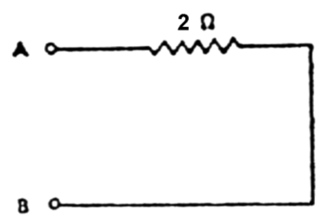
▶ $\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} +$

$\frac{1}{R_{eq}} = \frac{1}{4\ \Omega} + \frac{1}{4\ \Omega}$

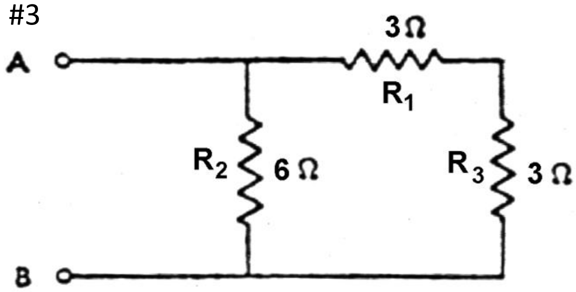
$\frac{1}{R_{eq}} = \frac{1}{2\ \Omega}$

$R_{eq} = 2\ \Omega$

Redrawn:



e.g. #3



$R_1 = 3\ \Omega$

$R_2 = 6\ \Omega$

$R_3 = 3\ \Omega$

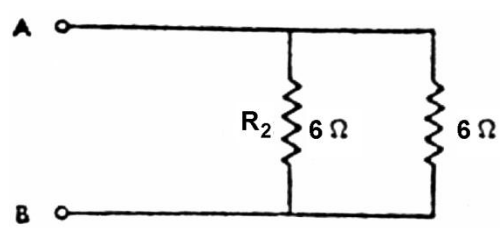
$R_1 + R_3$ are in series in an isolated part of the circuit, so we find the equivalent resistance here first:

▶ $R_{eq} = R_1 + R_3$

$= 3\ \Omega + 3\ \Omega$

$= 6\ \Omega$

Redrawn:



We have now simplified to a circuit with two resistors in parallel:

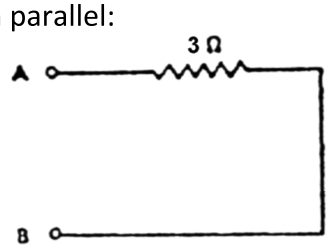
▶ $\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} +$

$\frac{1}{R_{eq}} = \frac{1}{6\ \Omega} + \frac{1}{6\ \Omega}$

$\frac{1}{R_{eq}} = \frac{1}{3\ \Omega}$

$R_{eq} = 3\ \Omega$

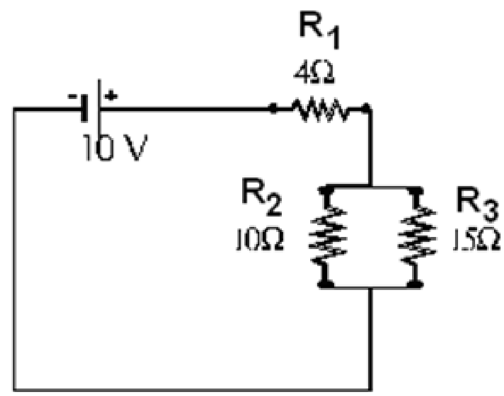
Redrawn:



Solving Circuits

When building circuits, we choose how much potential energy to give the electrons in the circuit (i.e. the voltage of the battery) and how and where this energy will be converted (by placing resistances and loads throughout). But before we build and turn on a circuit, we should know how much current will flow through each component to ensure it will work safely. We can do this by combining all we have learned about circuits thusfar:

e.g. #4 Find the current through each component in the circuit below.



First we need to find the equivalent resistance of the circuit:

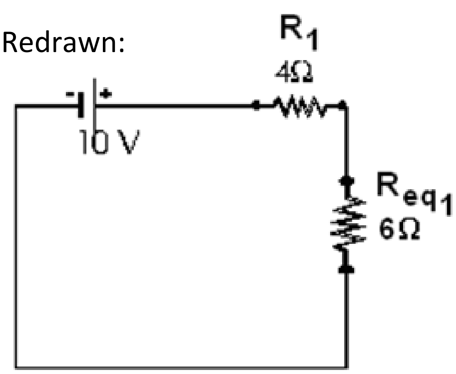
R_2 and R_3 are in parallel, so

► $\frac{1}{R_{eq}} = \frac{1}{10\ \Omega} + \frac{1}{15\ \Omega}$

$\frac{1}{R_{eq}} = \frac{5}{30\ \Omega}$

$R_{eq} = 6\ \Omega$

Redrawn:



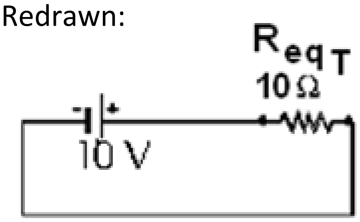
R_{eq1} and R_1 are in series, so

$R_{eqT} = R_1 + R_{eq1}$

$R_{eqT} = 4\ \Omega\ + 6\ \Omega$

$R_{eqT} = 10\ \Omega$

Redrawn:



Using Ohm's Law we can now find the current coming out of the battery:

$V = IR$

$I = \frac{V}{R} = \frac{10\ V}{10\ \Omega} = 1\ A$

R₁

Since R_1 is in series with the battery, we know that R_1 also has a current of 1 A

R_3

To find the current through R_3, we need to know how much energy electrons will lose passing through it (i.e. voltage), which is the energy not used by the R_1:

Energy lost through R_1:

$$V = IR$$
$$V = (1.0\ A)(4.0\ \Omega)$$
$$V = 4\ V$$

Therefore, energy lost through R_3:

$$V_{R3} = V_{Battery} - V_{R1}$$
$$V_{R3} = 10\ V - 4\ V$$
$$V_{R3} = 6\ V$$

Current through R_3:

$$V = IR$$
$$I = \frac{V}{R} = \frac{6\ V}{15\ \Omega} = 0.4\ A$$

R_2

Since R_3 and R_2 are in parallel, electrons lose the same amount of energy through either of them (i.e. 6 V). To find the current through R_2 we use Ohm's law again:

Current through R_2:

$$V = IR$$
$$I = \frac{V}{R} = \frac{6\ V}{10\ \Omega} = 0.6\ A$$

Alternatively, we could have solved for the current through R2 from knowing that the total current through the circuit is 1 A and that 0.4 A pass through R_3:

Current through R_2:

$$I_{R2} = I_{total} - I_{R3}$$
$$I_{R2} = 1.0\ A - 0.4\ A$$
$$I_{R2} = 0.6\ A$$

<u>Electrical Power</u>

Power – the rate of doing work (or transforming energy).

$$P = \frac{W}{\Delta t}$$ Units: Watts (W) 1 W = 1 J/s

Electrical power, or, the rate at which electrical energy is converted into other forms of energy, is a product of on how much energy a load will take from a single electron (voltage) and how many electrons pass through it with time (current):

$$P = \left(\frac{W}{Q}\right)\left(\frac{Q}{\Delta t}\right) = \frac{W}{\Delta t}$$

Therefore, $P = VI$