Module 4 Electrons, Waves & Photons

Unit 1 Charge & Current

4.1 Charge and current

This short section introduces the ideas of charge and current. Understanding electric current is essential when dealing with electrical circuits. This section does not lend itself to practical work but to introducing important ideas. The continuity equation ($I = Anev$) is developed using these key ideas. This section concludes with categorising all materials in terms of their ability to conduct.

Module 2 – Foundations of physics

2.1	Physical quantities and units
2.2	Making measurements and analysing data
2.3	Nature of quantities

Module 3 – Forces and motion

3.1	Motion
3.2	Forces in action
3.3	Work, energy and power
3.4	Materials
3.5	Newton's laws of motion and momentum

Module 4 – Electrons, waves and photons

You are here! →

4.1	Charge and current
4.2	Energy, power and resistance
4.3	Electrical circuits
4.4	Waves
4.5	Quantum physics

4.1 Charge & Current

- 4.1.1 Charge
- 4.1.2 Mean Drift Velocity

4.1.1 Charge

4.1.1 Charge

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) electric current as rate of flow of charge; $I = \dfrac{\Delta Q}{\Delta t}$

(b) the coulomb as the unit of charge

(c) the elementary charge *e* equals 1.6×10^{-19} C

(d) net charge on a particle or an object is quantised and a multiple of *e*

(e) current as the movement of electrons in metals and movement of ions in electrolytes

(f) conventional current and electron flow

(g) Kirchhoff's first law; conservation of charge.

What is Charge and Current?

Electric Current

- The rate of flow of charge.
- SI unit is the ampere (amp, A).

$$I = \frac{\Delta Q}{\Delta t}$$

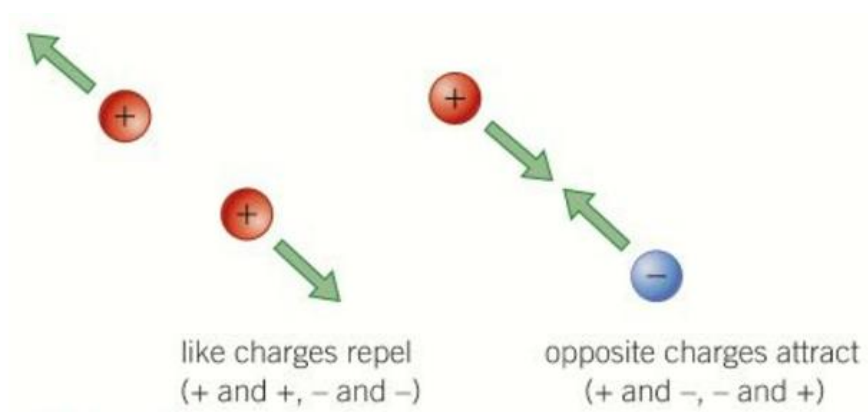
Where I is current (in amps), Q is charge (in coulombs), t is time (in seconds).

- Or, 1A is 1C of charge flowing past a point per second.

  $1A = 1Cs^{-1}$

Electric Charge

- Charge is a property of an object which causes it to experience a force when placed into an electromagnetic field.
- Charge can be positive or negative.
  - Opposite charged objects attract one another.
  - Equally charged objects repel one another.
- Electrons are negatively charged.
- Protons are positively charged.



Charge & the Coulomb

- The unit of electric charge is the coulomb, C.
- A coulomb is defined as the electric charge flowing past a point in 1 second when there is a current of 1 ampere.

$$\Delta Q = I\Delta t$$

- The charge, e, on one electron is -1.60x10^{-19}C
- A coulomb of charge is therefore the total charge carried by 6.25x10^{18} electrons.

Charge Carriers

- Any charged particle is a charge carrier.
  - Eg:
    - Proton = 1.60×10^{-19}C
    - Electron = -1.60×10^{-19}C
    - Sodium ion = 1.60×10^{-19}C
    - Chloride ion =-1.60×10^{-19}C
    - Magnesium ion = 3.20×10^{-19}C
  - In Chemistry we are used to seeing charges as 1+ or 2- etc.
    - These are relative charges measured against the elementary charge of the electron, *e*.

- If the current through a lamp is 6.2A, how many electrons pass one point in the lamp in 5 minutes?

$$\Delta Q = I\Delta t$$

$$\Delta Q = 6.2 \times 300 = 1860\text{C}$$

The number of electrons is then found by dividing this total charge by the elementary charge.

So, No of electrons = 1860C/1.60x10^{-19}C = 1.2x10^{22}

Quantised Charge

- Most objects become charged by gaining or losing electrons.
  - Gaining electrons produces a negative charge
  - Losing electrons leaves a positive charge

- The size of the overall net charge depends on how many electrons are gained/lost.

$$Q = \pm ne$$

- An object’s net charge can only have values which are integer multiples of e.

- Charge is therefore quantised

Net Charge /C	Relative Charge
1.92×10^{-18}	-12e
-3.20×10^{-19}	2e
9.60×10^{-19}	-6e

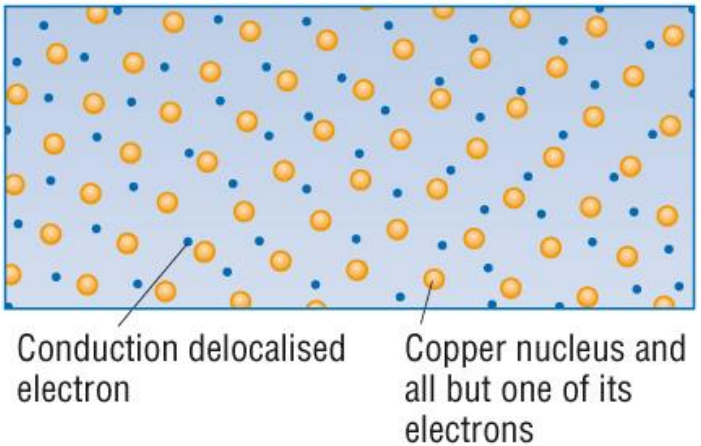
How can we model current?

Modelling current in wires

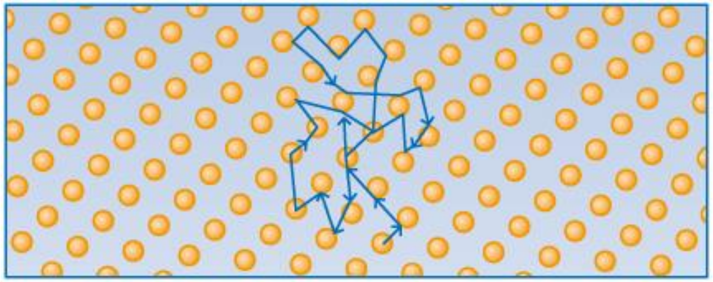
- Metals can be thought of as a crystal lattice of metal ions bathed in a sea of free, delocalised conduction electrons.

Current through a wire

- Metal atoms are arranged as a regular lattice.



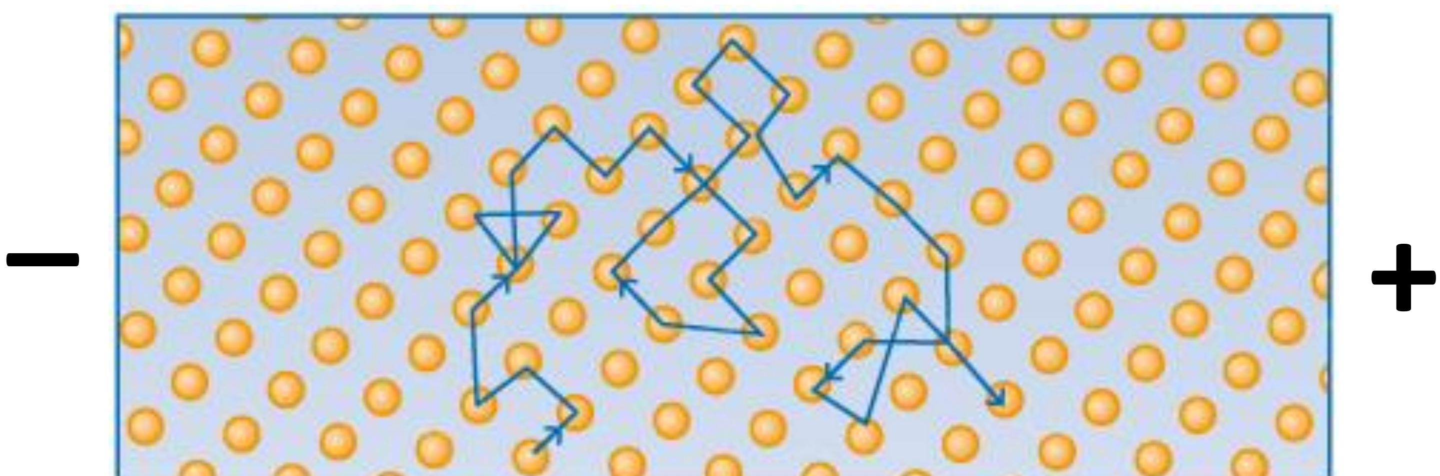
- Each atom has delocalised electrons which are free to jump from atom to atom.
  - Called conduction electrons.



Conduction in metals

- Making one end of the wire negatively charged and the other positive, the conducting electrons drift slowly along the wire as a current.
  - They can reach the dizzying speeds of $0.0002ms^{-1}$.
  - How far could they travel around a metre long circuit in 30 minutes?

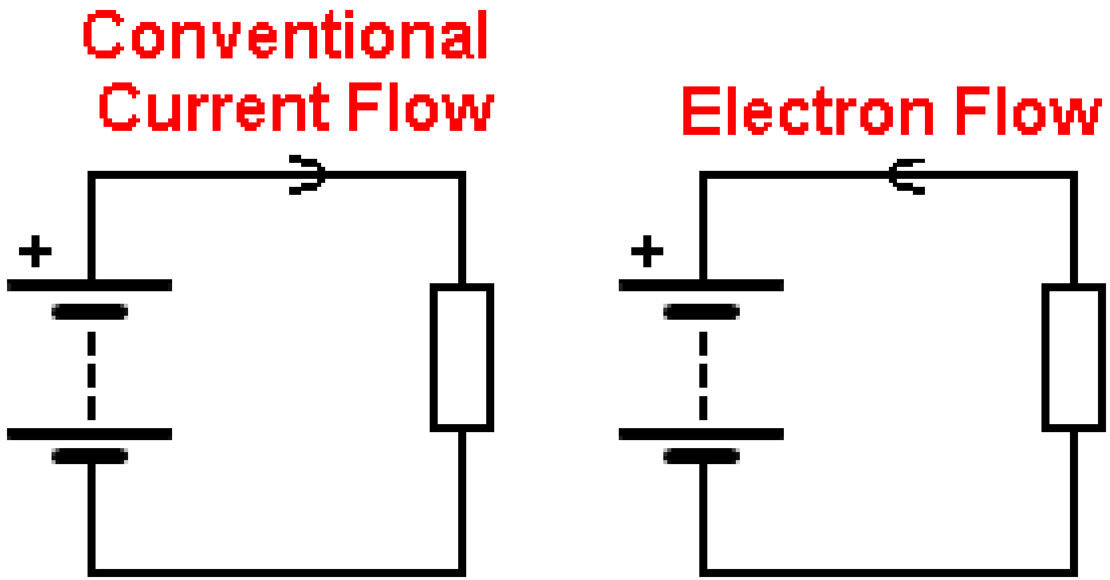
$s = vt = 0.0002 \times 60 \times 30 = 0.36m$



The strength of the current is related to:

- The number of electrons passing a point per second.
  - Affected by:
    - The drift velocity of the electrons.
    - The cross sectional area of the wire.

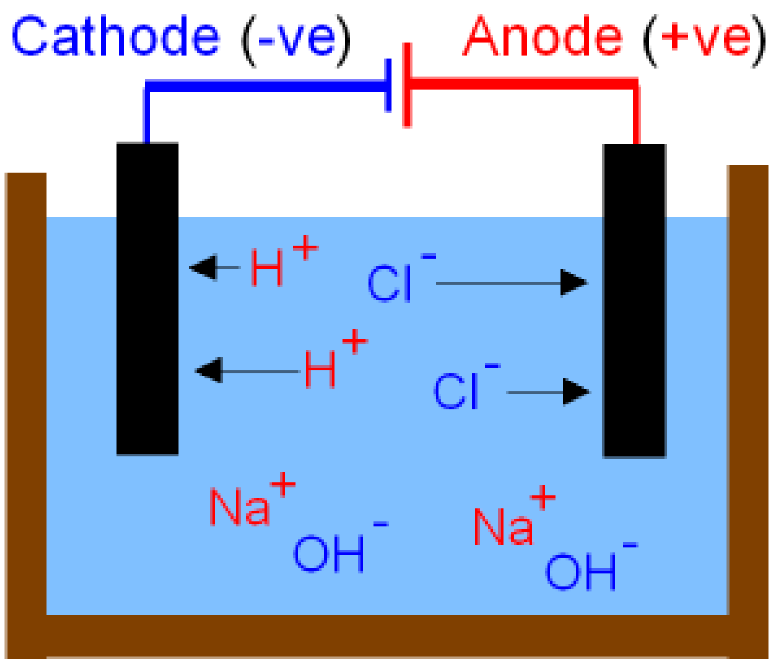
Conventional Current & Electron Flow



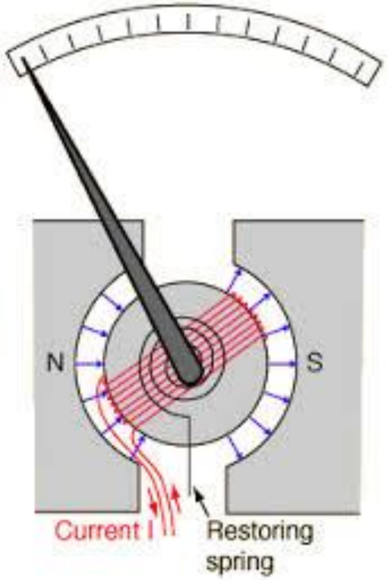
- Current was described long before the electron was discovered.
- It was always assumed that positive charge flowed from positive to negative.
- We now know it’s the opposite way round.

Current in Electrolytes

- Molten ionic compounds.
- Ionic solutions.
  - Eg. NaCl(aq)
  - What are the products here? And what causes electrons to flow through the wires?



Ammeters – measure current



- Placed in series.
- Have negligible resistance.
- Traditional ammeters
  - Use the magnetic field produced by a coil to move a pointer (remember the left hand rule?).
- Digital ammeters
  - Use a current sensor

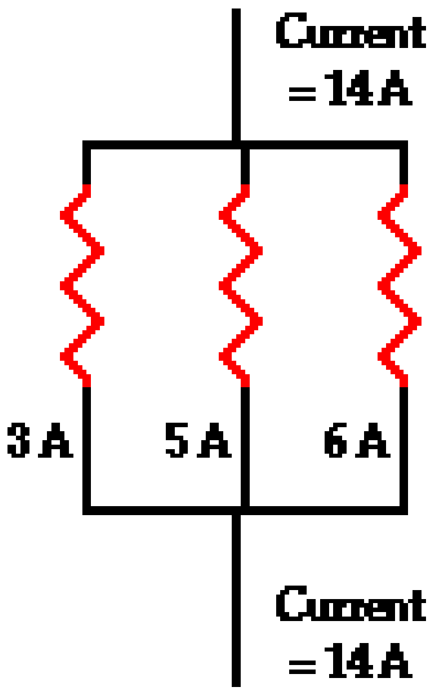
What is Kirchhoff’s first law?

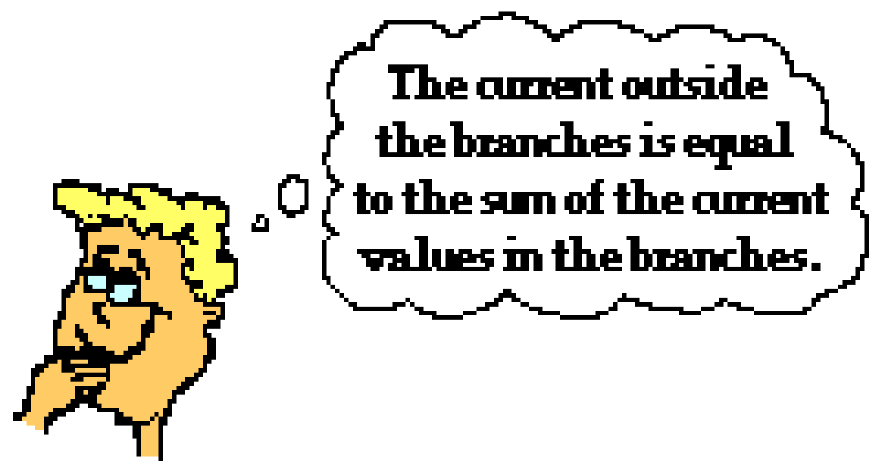
- In any interaction, the total charge before & after the interaction must be conserved.
- So charge, like mass, cannot be created or destroyed.
- Kirchhoff’s law deals with current rather than charge directly but it means the same thing.
- At any electrical junction the total current entering the junction is the same as the total current leaving the junction.

$$\sum I_{in} = \sum I_{out}$$

Kirchhoff’s First Law

The sum of the currents entering a junction is always equal to the sum of the currents leaving the junction.





4.1.1 Charge (review)

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4.1.2 Mean Drift Velocity

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Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) mean drift velocity of charge carriers

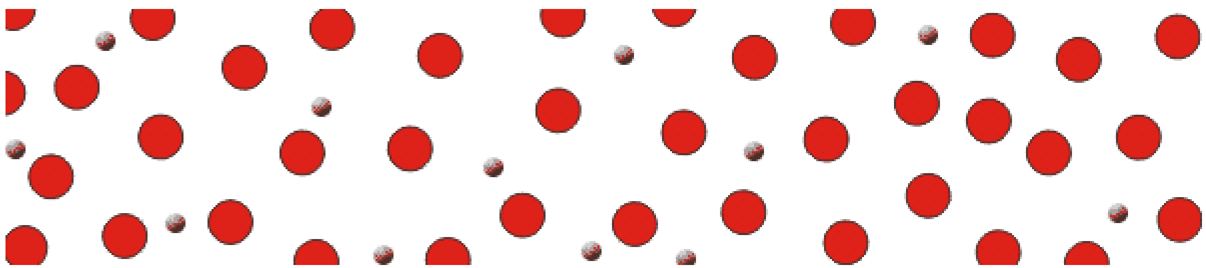
(b) $I = Anev$, where n is the number density of charge carriers

(c) distinction between conductors, semiconductors and insulators in terms of n.

How can we calculate the mean electron drift velocity?

Mean Drift Velocity

- We saw earlier how conduction electrons in a wire move randomly but gradually drift when a voltage is applied.
  - They only move short distances before colliding into another atom.



- We can calculate the mean velocity of conduction electrons if we know:
  - The cross sectional area (or thickness) of the wire.
  - The number density of atoms within it (number of atoms per unit volume).
  - The number of conduction electrons each atom provides.
  - The current through the wire.

Calculating Drift Velocity

- The current through the above wire is 6A.
  - Which means a charge flow of $6Cs^{-1}$. (since Q=It)
  - The number of conduction electrons needed to provide 6C is $6/1.6x10^{-19}$ which is $3.75x10^{19}$ electrons. (since $e=1.6x10^{-19}$)
  - These electrons occupy the shaded area on the diagram, and therefore will travel this length in one second.
  - If we want to know the drift velocity, v, we just need to know the length of this section of wire.

Calculating Drift Velocity

Velocity, v, = s/t. Therefore s=vt.

The volume of this wire = As = Avt.

If there are n conduction electrons per m^3 of wire (number density)

And each electron has a charge, e, of -1.6×10^{-19},

The total charge flowing through this section of wire in a second is n *x* volume of wire *x* e.

So, total charge, Q = nAvte.

Since Q=It, It = nAvte.

Cancel the t: I = nAve

So, v = I/nAe

In this example,

$$v = 6.0 / 8.0 \times 10^{28} m^{-3} \times 2.0 \times 10^{-6} m^2 \times 1.6 \times 10^{-19} C$$

$$= 2.3 \times 10^{-4} ms^{-1} \text{ or } 0.23 mms^{-1}$$

Equations to learn and use

$$I = nAve$$

$$v = \frac{I}{nAe}$$

Where:

I = Current, amps

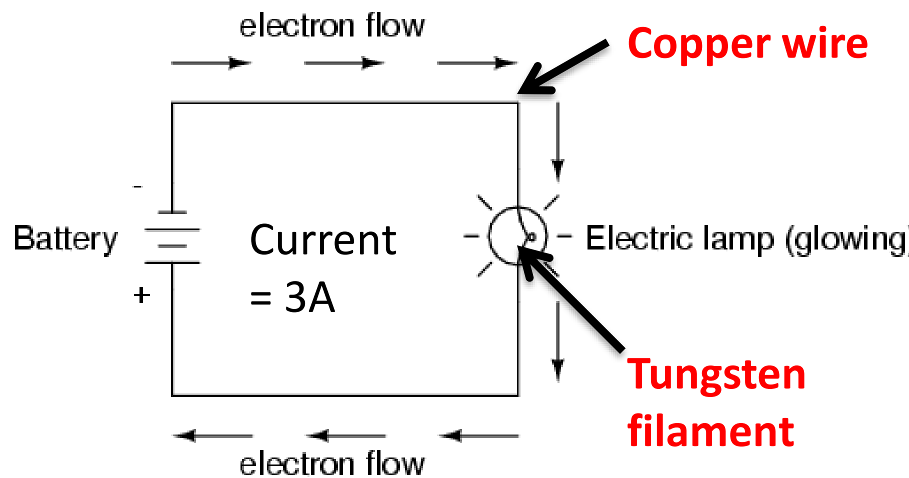
n = Number density of conduction electrons

A = Cross sectional area of wire, m^2

v = Mean drift velocity of electrons, ms^{-1}

e = Charge on one electron, C

What happens to the drift velocity through the filament of a lamp?



- Copper Wire:
  - Thickness = 1mm diameter
  - Atomic number density = $8.0 \times 10^{28} m^{-3}$
  - Conduction electrons per atom = 1

$$V_{Cu} = 2.9 \times 10^{-4}\ ms^{-1}$$

- Tungsten Filament:
  - Thickness = 0.1mm diameter
  - Atomic number density = $6.3 \times 10^{28} m^{-3}$
  - Conduction electrons per atom = 1

$$V_{W} = 3.8 \times 10^{-2}\ ms^{-1}$$

This is why the filament glows.

Comparing Drift Velocities

- Good electrical conductors:
  - Large number of conduction electrons.
  - Large number densities
- Good electrical insulators:
  - Few or no conduction electrons.
  - Electron number densities are close to zero
- Semiconductors:
  - Have intermediate properties.
  - The number density can be altered by adding an impurity to the material – this is called doping.

- Through which of these 3 materials do electrons drift the fastest?
  - Semiconductor (lower number density, but not zero number density)

4.1.2 Mean Drift Velocity (review)

4.1.2 Mean drift velocity

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Module 4 – Electrons, waves and photons

Complete! →

- 4.1 Charge and current
- 4.2 Energy, power and resistance
- 4.3 Electrical circuits
- 4.4 Waves
- 4.5 Quantum physics