Electricity & Magnetism

Current of Electricity

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Recap……

- Types of electricity
- **Current Electricity**: Net flow of charges in a certain direction
- **Static Electricity**: No net flow of charges in a certain direction

- Matter can be classified into 3 types according to their electrical properties:

- **Conductors** – Materials which have mobile charge carriers, mainly electrons and ions which will drift to constitute an electric current under the effect of an applied electric field. Hence they can conduct electricity. Examples include metals and electrolyte solutions.
- **Insulators** – Materials which have no mobile charge carriers that can drift under the effect of an applied electric field. Hence they cannot conduct electricity. Examples include rubber, wood and plastic.
- **Semiconductors** – Materials which have intermediate electrical conductivity which vary substantially with temperature. Examples include Germanium, Silicon.

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Show an understanding that electric current is the rate of flow of charged particles.

- All matter is made up of tiny particles called atoms, each consisting of a positively charged nucleus with negatively charged electrons moving around it.
- Charge is measured in units called coulombs (C). The charge on an electron is -1.6×10^{-19} C.
- Normally atoms have equal number of positive and negative charges, so that their overall charge is zero.
- For some atoms, it is relatively easy to remove an electron, leaving an atom with an unbalanced number of positive charges. This is called positive ion.

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Show an understanding that electric current is the rate of flow of charged particles. (continued from previous slide)

- Atoms in metals have one or more electrons which are not held tightly to the nucleus.
- These free (or mobile) electrons wander at random throughout the metal.
- But when a battery (or source) is connected across the ends of the metal, the free electrons drift towards the positive terminal of the battery (or source) producing an electric current.

Show an understanding that electric current is the rate of flow of charged particles. (continued from previous slide)

- The size of the electric current is given by the rate of flow of charge and is measured in units called amperes with symbol A.
- A current of 3 amperes means that 3 coulombs pass a point in the circuit every second. In 5 seconds, a total charge of 15 coulombs will have passed the point.

Charge is quantised

Because electric charge is carried by particles, it must come in amounts which are multiples of e. So, for example, 3.2×10^{-19} C is possible, because this is $+2e$, but 2.5×10^{-19} C is impossible, because this is not an integer multiple of e.

We say that charge is 'quantised'; this means that it can only come in amounts which are integer multiples of the elementary charge. If you are studying chemistry, you will know that ions have charges of $\pm e$, $\pm 2e$, etc. The only exception is in the case of the fundamental particles called quarks, which are the building blocks from which particles such as protons and neutrons are made. These have charges of $\pm\frac{1}{3}e$ or $\pm\frac{2}{3}e$. However, quarks always appear in twos or threes in such a way that their combined charge is zero or a multiple of e.

An equation for current

Copper, silver and gold are good conductors of electric current. There are large numbers of conduction electrons in a copper wire – as many conduction electrons as there are atoms. The number of conduction electrons per unit volume (e.g. in 1 m^3 of the metal) is called the **number density** and has the symbol n. For copper, the value of n is about 10^{29} m^{-3}.

Figure 9.9 shows a length of wire, with cross-sectional area A, along which there is a current I. How fast do the electrons have to travel? The following equation allows us to answer this question:

$$I = nAvq$$

Here, v is called the **mean drift velocity** of the electrons and q is the charge of each particle carrying the current. Since these are usually electrons, we can replace q by e, where e is the elementary charge. The equation then becomes:

$$I = nAve$$

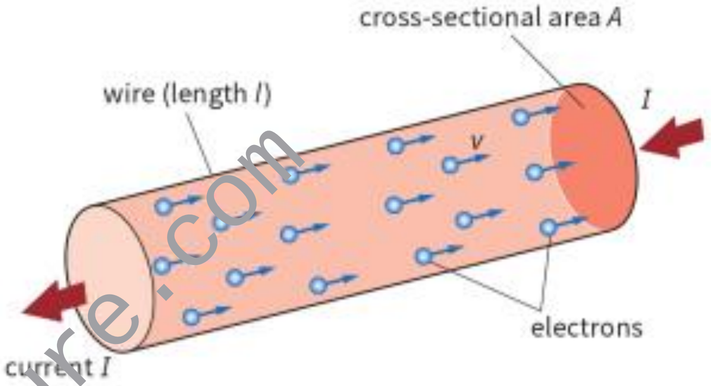


Figure 9.9 A current I in a wire of cross-sectional area A. The charge carriers are mobile conduction electrons with mean drift velocity v.

Deriving $I = nAve$

Look at the wire shown in Figure 9.9. Its length is l. We imagine that all of the electrons shown travel at the same speed v along the wire.

Now imagine that you are timing the electrons to determine their speed. You start timing when the first electron emerges from the right-hand end of the wire. You stop timing when the last of the electrons shown in the diagram emerges. (This is the electron shown at the left-hand end of the wire in the diagram.) Your timer shows that this electron has taken time t to travel the distance l.

In the time t, all of the electrons in the length l of wire have emerged from the wire. We can calculate how many electrons this is, and hence the charge that has flowed in time t:

number of electrons = number density × volume of wire

$$= n \times A \times l$$

charge of electrons = number × electron charge

$$= n \times A \times l \times e$$

We can find the current I because we know that this is the charge that flows in time t, and current = charge/time:

$$I = n \times A \times l \times e / t$$

Substituting v for l / t gives

$$I = nAve$$

The moving charge carriers that make up a current are not always electrons. They might, for example, be ions (positive or negative) whose charge q is a multiple of e. Hence we can write a more general version of the equation as

$$I = nAvq$$

Worked example 3 shows how to use this equation to calculate a typical value of v.

WORKED EXAMPLE

3 Calculate the mean drift velocity of the electrons in a copper wire of cross-sectional area $5.0 \times 10^{-6}\,\text{m}^2$ carrying a current of 1.0 A. The electron number density for copper is $8.5 \times 10^{28}\,\text{m}^{-3}$.

Step 1 Rearrange the equation $I = nAve$ to make v the subject:

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

Step 2 Substitute values and calculate v:

$$v = \frac{1.0}{8.5 \times 10^{28} \times 5.0 \times 10^{-6} \times 1.6 \times 10^{-19}}$$

$$= 1.47 \times 10^{-5}\,\text{m s}^{-1}$$

$$= 0.015\,\text{mm s}^{-1}$$

Slow flow

It may surprise you to find that, as suggested by the result of Worked example 3, electrons in a copper wire drift at a fraction of a millimetre per second. To understand this result fully, we need to closely examine how electrons behave in a metal. The conduction electrons are free to move around inside the metal. When the wire is connected to a battery or an external power supply, each electron within the metal experiences an electrical force that causes it to move towards the positive end of the battery. The electrons randomly collide with the fixed but vibrating metal ions. Their journey along the metal is very haphazard. The actual velocity of an electron between collisions is of the order of magnitude $10^5\,\text{m s}^{-1}$, but its haphazard journey causes it to have a **drift velocity** towards the positive end of the battery. Since there are billions of electrons, we use the term **mean drift velocity** v of the electrons.

Figure 9.10 shows how the mean drift velocity of electrons varies in different situations. We can understand this using the equation:

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

- If the current increases, the drift velocity v must increase. That is:

  $v \propto I$

- If the wire is thinner, the electrons move more quickly for a given current. That is:

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

  There are fewer electrons in a thinner piece of wire, so an individual electron must travel more quickly.

- In a material with a lower density of electrons (smaller n), the mean drift velocity must be greater for a given current.

That is:

$$v \propto \frac{1}{n}$$

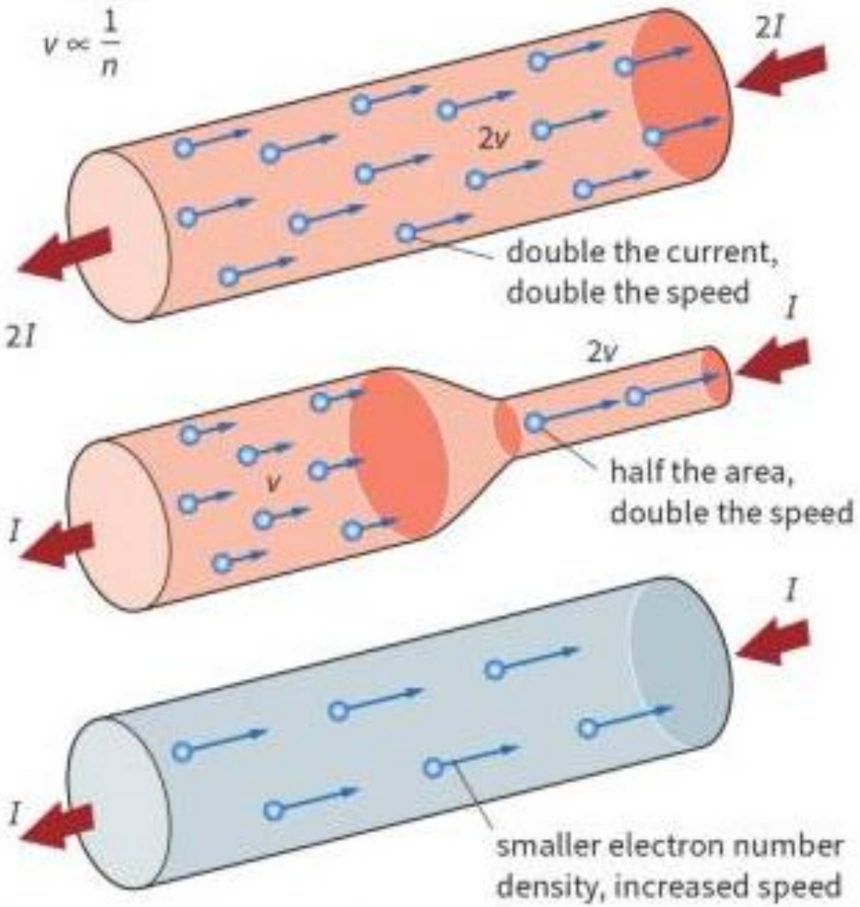


Figure 9.10 The mean drift velocity of electrons depends on the current, the cross-sectional area and the electron density of the material.

It may help you to picture how the drift velocity of electrons changes by thinking about the flow of water in a river. For a high rate of flow, the water moves fast – this corresponds to a greater current I. If the course of the river narrows, it speeds up – this corresponds to a smaller cross-sectional area A.

Metals have a high electron number density – typically of the order of 10^{28} or $10^{29}\,m^{-3}$. Semiconductors, such as silicon and germanium, have much lower values of n – perhaps $10^{23}\,m^{-3}$. In a semiconductor, electron mean drift velocities are typically a million times greater than those in metals for the same current. Electrical insulators, such as rubber and plastic, have very few conduction electrons per unit volume to act as charge carriers.

Electric current

- **Electric current** is the rate of flow of electric charge.
- Mathematically, $I = \frac{Q}{t}$ *where*

I is the electric current (unit: ampere, symbol: A);

Q is the electric charge (unit: coulomb, symbol: C);

t is the time taken (unit: second, symbol: s)

Charge & Coulomb

- From the definition of electric current $I = \frac{Q}{t}$ we obtain, $Q = It$.
- **Electric charge** flowing through a section of a circuit is the product of the electric current and the time that it flows.

- Q = It, substituting in units we obtain the following :
- 1 C = (1 A) (1 s) = 1 A s
- **One coulomb** is the quantity of electric charge that passes through a section of a circuit when a steady current of one ampere flows for one second.

Solve problems using the equation *Q* = *It*

Example 1

Given that the electric current flowing through a circuit is 0.76 mA, calculate the electric charge which passes each section of the circuit over a time of 60 s.

Solution:

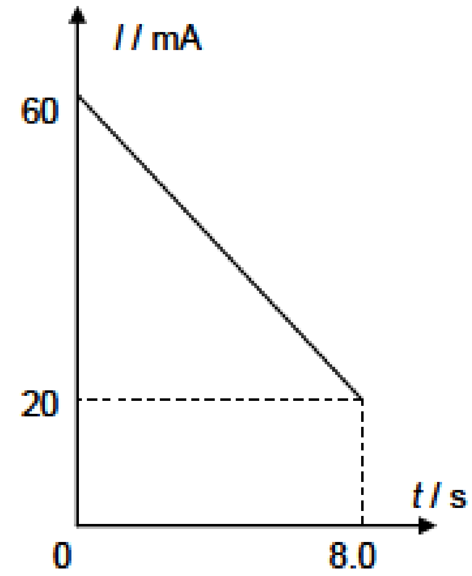
$$[Q = It]$$

$$Q = (0.76 \times 10^{-3})(60) = 0.0456 = 4.56 \times 10^{-2}\,\text{C}$$

Solve problems using the equation *Q* = *It*

Example 2

Over a time of 8.0 s, the electric current flowing through a circuit component is reduced uniformly from 60 mA to 20 mA. Calculate the charge that flows during this time.



Solution:

Charge = area under current-time graph

$$= \tfrac{1}{2}(8.0)(60+20)(10^{-3}) = 0.32\ \text{C}$$

Resistance and Ohm

Ohm's Law states that the current through the conductor is directly proportional to the potential difference between its ends provided its temperature and other physical conditions remain constant.

Mathematically

$$I \propto V \quad \Rightarrow \quad V = RI \quad \Rightarrow \quad R = \frac{V}{I}$$

The proportionality constant R in the equation is the electrical resistance of the device. It is constant for a metallic conductor under steady physical conditions. Materials which obey Ohm's law are called ohmic conductors.

Resistance of a conductor is defined as the ratio of the potential difference across it to the current flowing through it.

From $R = \frac{V}{I}$, $1\ \Omega = 1\ V\ A^{-1}$ defines the ohm.

The **ohm** is the resistance of a conductor if a current of one ampere flows through when there is a potential difference of one volt across it.

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Solve problems using
$P = VI$, $P = I^2R$, $V = IR$

Example 5

A 12 V 24 W bulb is connected in series with a variable resistor and a 18 V battery of negligible internal resistance. The variable resistor is adjusted until the bulb operates at its normal rating.

Determine
- (i) the current in the bulb
- (ii) the resistance of the bulb
- (iii) the p.d. across the variable resistor;
- (iv) the power dissipation in the variable resistor.

Solution:

(i) $P = VI$
$24 = (12)I$
$I = 2.0$ A

(ii) $V = IR$
$12 = (2.0)R$
$R = 6.0\ \Omega$

(iii) p.d. across variable resistor = 18 – 12 = 6.0 V

(iv) $P = VI = (6.0)(2.0) = 12$ W

Resistance & Resistivity

The resistance *R* of a sample is directly proportional to its length *l* and inversely proportional to its cross-sectional area *A*.

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

The relationship could be expressed as an algebraic equation by introducing a constant of proportionality as follows:

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

The constant *ρ* is now recognised as a property of the material and is called its **resistivity**. Hence

$$\rho = \frac{RA}{l}$$

where *ρ* is the resistivity of the material, in Ω m

R is the resistance of the sample, in ohms (Ω)

A is the cross-section area of the sample, in m^2

l is the length of the sample, in metres (m)

Resistivity is useful when comparing various materials on their ability to conduct electricity. A high resistivity means a sample of the material is a poor conductor. A low resistivity means a sample of the material is a good conductor.

Resistivity

- Resistivity is defined as the electrical property of a material that determines the resistance of a piece of given dimensions.

- It is equal to $\rho = \frac{RA}{l}$ where R is the resistance, A the cross-sectional area, and l the length, and is the reciprocal of conductivity. It is measured in ohm metres. It is denoted by the symbol **ρ.**

Solve problems using $R = \frac{\rho L}{A}$

Example 6

The resistivity of a material is $3.1 \times 10^{-5}\ \Omega$ m. Determine the resistance of a sample of the material given that its length is 20 cm and its cross-section area is 2.0 mm^2.

Solution:

$$R = \frac{\rho l}{A} = \frac{(3.1 \times 10^{-5})(0.20)}{(2.0)(0.001)^2} = 3.1\Omega$$

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Potential difference and Volt

- Defining p.d in terms of energy:
  - The potential difference between two points in a circuit is defined as the electrical energy converted to other forms of energy per unit charge passing between the two points.
- Alternatively, defining p.d in terms of power:
  - The p.d. between two points in a circuit is defined as the rate of conversion of electrical energy to other forms of energy per unit current flowing between the two points.

Potential difference and Volt (continued)

In terms of energy:

$$\text{potential difference (p.d.)} = \frac{\text{energy converted}}{\text{charge}}$$

$$\text{hence } \boldsymbol{V} = \frac{\boldsymbol{W}}{\boldsymbol{Q}} \text{ or } W = QV.$$

In terms of power:

$$\text{potential difference (p.d.)} = \frac{\text{power converted}}{\text{current}}$$

$$\text{hence } V = \frac{P}{I} \text{ or } \boldsymbol{P} = \boldsymbol{VI}.$$

where V is the p.d., in volts (V)
W is the energy converted, in joules (J)
Q is the electric charge moved, in coulombs (C)
P is the power converted, in watts (W)
I is the electric current flowing, in amperes (A)

Since $V = IR$ from learning outcome (h), $\boldsymbol{P} = \boldsymbol{I^2R}$.

From $V = \frac{W}{Q}$, 1 V = 1 J C^{-1} defines the volt (in terms of energy).

Potential difference and Volt (continued)

The **volt** is the potential difference between two points in a circuit if one joule of electrical energy is converted to other forms of energy when one coulomb of charge passes between the two points.

Alternatively, from $P = VI$, 1 V = 1 W A^{-1} defines the volt (in terms of power).

The **volt** is the potential difference between two points in a circuit if one watt of electrical power is converted to other forms of power when one ampere of current passes between the two points.

Potential difference and Volt (continued)

Note:

- Since the unit for p.d. is volt, p.d. is frequently called voltage.
- The p.d. can only be used if the two points are stated clearly. For a single circuit component, the two points are usually the two ends of the component hence the p.d. across the component.
- Sometimes the term "potential at a point" in a circuit is used. This has meaning only if there is a defined reference point for zero potential e.g. the electrical **earth** has zero potential.

Just for your info : The real Earth is electrically neutral. This means that it has the same number of electrons and protons, so their charges cancel out overall. Scientifically, we describe this by saying that the Earth has an Electric Potential of zero.

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Solve problems using $V = \frac{W}{Q}$

Example 4

An immersion heater is rated at 3000 W and is switched on for 2000 s. During this time a charge of 25 kC is supplied to the heater. Determine the potential difference across the heater.

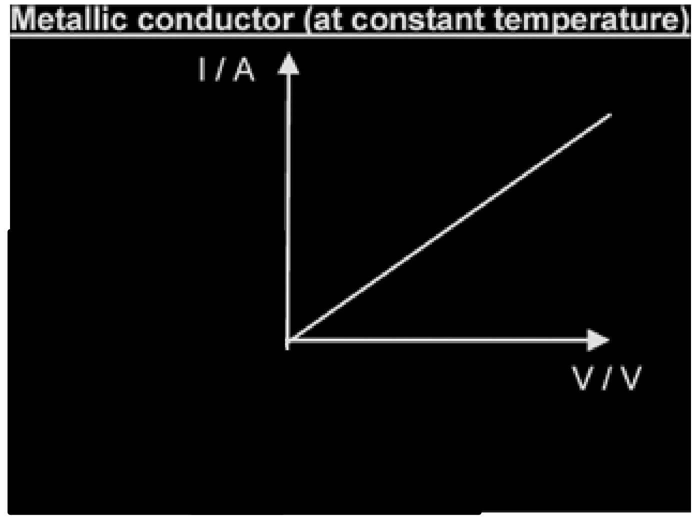
Solution:

$$V = \frac{W}{Q} = \frac{(3000)(2000)}{25000} = 240\ \text{V}$$

Sketch and explain
the *I-V characteristics*
of
***a metallic conductor at* constant temperature,**
a semiconductor diode
and
a filament lamp.

Sketch and explain the *I-V characteristics of a metallic conductor at* constant temperature

1) Metallic conductor at constant temperature



- The *I-V* characteristic of a metallic conductor at constant temperature is a straight line through the origin. This implies constant *I-V* ratio, i.e. constant resistance. Therefore a metallic conductor at constant temperature is an ohmic conductor.
- In terms of the movement of charge carriers, resistance in metallic conductors arises from the reduction in the drift velocity of free electrons due to collision with lattice ions. If the temperature of the conductor is kept constant, the lattice ion vibrations will remain the same hence its resistance will remain the constant.
- In short, the resistance of a metallic conductor is constant at constant temperature (ohmic conductor).

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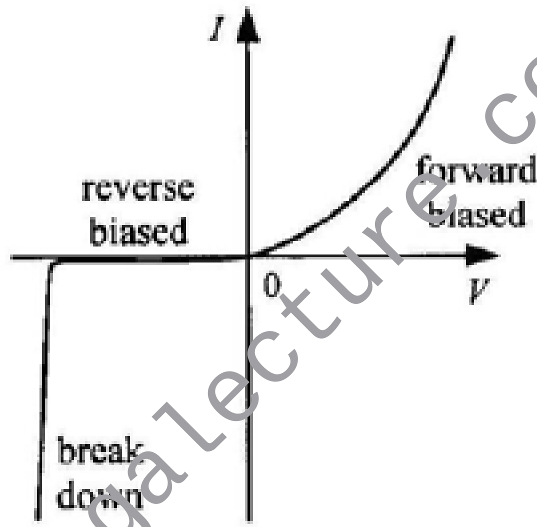
Sketch and explain the *I-V characteristics of* a semiconductor diode

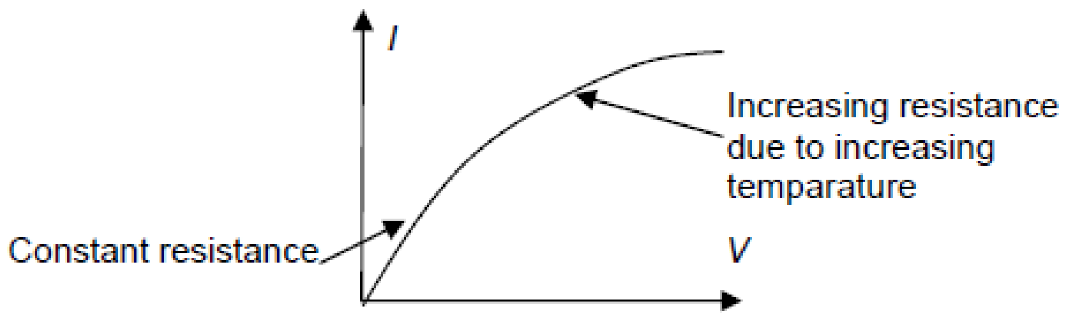
2) Semiconductor diode



- A diode is a device that has a low resistance in one direction (forward-biased direction) and a very high resistance in the other direction (reverse-biased direction).
- The *I-V* characteristic of a forward-biased semiconductor diode is similar to that of a thermistor, i.e. resistance decreases as p.d. increases.
- The *I-V* characteristic of a reverse-biased semiconductor diode is nearly zero. If reverse-biased p.d. is too high, the diode will break down and conduct electricity.

Sketch and explain the *I-V characteristics of a* filament lamp.

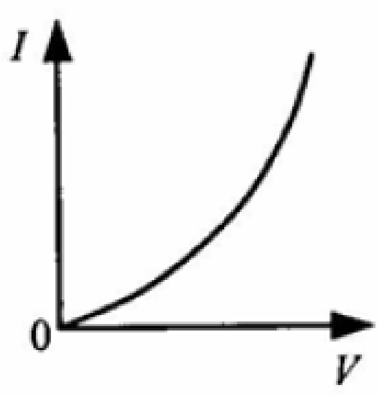
3) Filament lamp

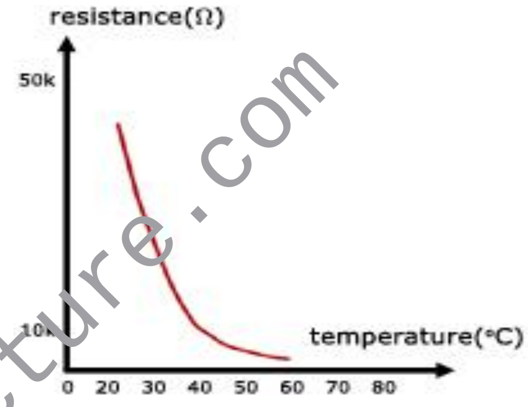


- A filament lamp contains a long thin wire made of metal with high melting point (e.g. tungsten).
- With low p.d. across the filament lamp, low current flowing through it and the heating effect is insignificant hence the resistance is fairly constant.
- As the p.d. across a filament lamp increases, current increases. Heating effect is significant resulting in temperature increase.
- The resistance of metals increases with temperature. Hence, decreasing *I-V* gradient.
- In terms of the movement of charge carriers, the lattice ion vibrations will be more at higher temperature. There will be more reduction in the drift velocity of electrons due to collision with lattice ions hence current will be lower and resistance will be higher.
- In short, the resistance of a filament lamp increases as the p.d. applied across it increases.

The temperature characteristic of a thermistor

Thermistor *I-V* characteristic and temperature characteristic





- A thermistor is a resistor made of semiconductors.
- With low p.d. across the thermistor, low current flowing through it and the heating effect is insignificant hence the resistance is fairly constant.
- As the p.d. across a thermistor increases, current increases. Heating effect is significant resulting in temperature increase.
- The resistance of semiconductors decreases with temperature. Hence, increasing *I-V* gradient.
- In terms of the movement of charge carriers, the lattice ion vibrations will be more at higher temperature. There will be more reduction in the drift velocity of charge carriers due to collision with lattice ions. However the concentration of charge carriers in semiconductors increases significantly with temperature. Hence the overall effect is a reduction in resistance.
- In short, the resistance of a thermistor decreases as its temperature increases.

E.M.F in terms of the energy transferred by a source in driving unit charge round a complete circuit

Movement of charge carriers is possible only if they possess energy and are allowed to dissipate their energy. Sources like batteries and generators provide the energy to the charge carriers. Available path(s) for charge carriers to dissipate their energy cause their movement.

Defining in terms of energy:

The **electromotive force (e.m.f.)** of a source is defined as the non-electrical energy converted to electrical energy per unit charge driven through the source.

Defining in terms of power:

The **electromotive force (e.m.f.)** of a source is defined as the non-electrical power converted to electrical power per unit current delivered by the source.

The SI unit of e.m.f. is same as that of potential difference, i.e. the volt. (Recall that $1\ V = 1\ J\ C^{-1}$ or $1\ W\ A^{-1}$)

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E.M.F in terms of the energy transferred by a source in driving unit charge round a complete circuit (continued from previous slide)

Mathematically, $\boldsymbol{E} = \frac{\boldsymbol{W}}{\boldsymbol{Q}}$ or $\boldsymbol{E} = \frac{\boldsymbol{P}}{\boldsymbol{I}}$

where *E* is the e.m.f. of the source, in volts (V)
W is the energy converted, in joules (J)
Q is the electric charge moved, in coulombs (C)
P is the power converted, in watts (W)
I is the electric current delivered, in amperes (A)

Examples include:

- In a battery, chemical energy converted to electrical energy through chemical reactions.
- In a generator, mechanical energy (in the form of rotational kinetic energy) is converted to electrical energy.

Distinguish between e.m.f. and p.d. in terms of energy considerations

- The electromotive force (e.m.f.) of a source is defined using the non-electrical energy converted to electrical energy while the potential difference (p.d.) between two points is defined using electrical energy converted to non-electrical energy.

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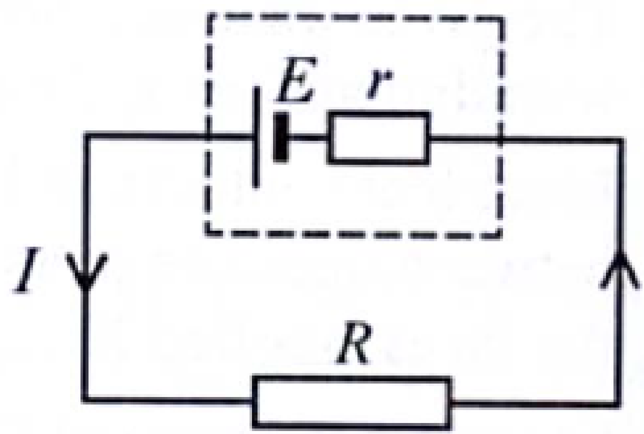
The effects of the internal resistance of a source of e.m.f. on the terminal potential difference and output power.

- In practice, no energy source (battery or generator) is perfect.
- Some of the electrical energy delivered by a source is always dissipated within itself.
- The source is said to have internal resistance. When the external load is large, the internal resistance has negligible effect.
- When the external load is not large, the internal resistance can be depicted as a series resistor within the source as shown in the diagram in next slide.

The effects of the internal resistance of a source of e.m.f. on the terminal potential difference and output power.

(continued from previous slide)



The energy delivered by the source is then shared between its internal resistance and external load,

i.e. energy supplied = energy dissipated (external + internal).

$$EIt = I^2Rt + I^2rt$$

$$\Rightarrow \quad E = IR + Ir$$

$$\Rightarrow \quad E = I(R+r)$$

E = V

V x I = P

The **terminal p.d.** is the potential difference across the source. It is equivalent to the potential difference across the external circuit.

Hence terminal p.d. is $V = IR = E - Ir$

where V is the terminal p.d., in volts (V)

E is the e.m.f. of the source, in volts (V)

I is the electric current delivered, in amperes (A)

R is the resistance of the external circuit, in ohms (Ω)

r is the internal resistance of the source, in ohms (Ω)

The effects of the internal resistance of a source of e.m.f. on the terminal potential difference and output power.

(continued from previous slide)

It can be deduced that when the source is connected to an external circuit, the terminal p.d. of the source is reduced by the amount Ir.

$$V = E - Ir$$

When the current I through the source is zero (such as when the external circuit is open) then terminal p.d. V will be equal to the e.m.f. E.

I in the above equation becomes Zero

When the internal resistance is negligible, the terminal p.d. will be approximately equal to the e.m.f. E.

Alternatively, viewing in terms of power, the power delivered by the source is shared between its internal resistance and external load,

i.e. power supplied = power dissipated (external + internal).

$$P_E = P_R + P_r$$

$$EI = I^2R + I^2r$$

The power dissipated internally ($P_r = I^2r$) is wasted in heating up the energy source. Only the power that is dissipated externally ($P_R = I^2R$) is available to the external circuit so the efficiency of the source is always below 100%.

$$\text{Efficiency } \eta = \frac{\text{useful power}}{\text{total power}} = \frac{VI}{EI} = \frac{I^2R}{I^2(R+r)} = \frac{R}{R+r}$$

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Show an understanding of the effects of the internal resistance of a source of e.m.f. on the terminal potential difference and output power.

Example 7

A battery of e.m.f. 12 V and internal resistance 0.014 Ω delivers a 2.0 A current when first connected to a motor. Calculate the resistance of the motor.

Solution:

$$E = I(R+r) \Rightarrow 12 = 2.0(R + 0.014) \Rightarrow \mathrm{R} = 5.99\ \Omega$$