Suggest reasons for the following observations :-

(a) Gold is used for microchip contacts instead of copper even though copper has a smaller resistivity (less resistance).

Gold is less susceptible to corrosion. Corrision increases the resistance of the metal.

(b) Constantan is used in standard resistors.

Because resistivity of constantan changes little with temperature. Use to calibre other types of resistors.

Worked Example 5.1

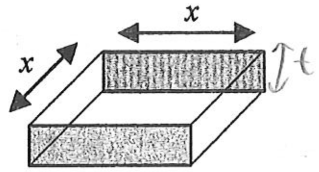
A sample of resistive material is prepared in the form of a thin square slab of side x. For a given thickness, the resistance between opposite edge faces of the sample (shown shaded in figure below) is:

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

(A) proportional to x^2 (B) proportional to x

√(C) independent of x (D) inversely proportional to x

(E) inversely proportional to x^2



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

$= \frac{\rho x}{x t}$

$= \frac{\rho}{t}$

6 Electrical Power

In this section, students are required to:

$V = IR$

(a) recall and use $P = VI$, $P = I^2R$.

- We have earlier shown that both energy and power can be expressed from potential difference.

$$P = \frac{W}{t}$$

Starting from $V = \frac{W}{Q}$ or $W = VQ$ we get $P = \frac{VQ}{t} = VI$

- Thus, the power or the rate of energy of conversion in an electrical device when there is a potential difference of V across it and a current I is passing through it can be expressed as

$$\boxed{P = IV}$$

passing through device not battery

- For a resistor, alternate forms of power expression can be obtained using the definition of resistance R.

$$\boxed{P = I^2R \quad \textit{and} \quad P = \frac{V^2}{R}}$$

- To measure consumption of electrical energy, the unit kilowatt-hour (kWh) is used instead of joule. The kilowatt-hour is the electrical energy transferred by a 1kW device in 1 hour. In Singapore, 1 kWh of electrical energy costs about 17 cents.

$P = \frac{E}{t}$ $E = Pt$

Worked Example 6.1

$1 kWh = 1000W \times 3600s = 3600000 J$

An electrical heating element is to be designed so that the power dissipated will be 750 W when connected to a 240 V supply.

(a) Calculate the resistance of the wire needed.

(b) The element is to be made from nichrome ribbon 1.0 mm wide and 0.05 mm thick, calculate the length of ribbon required (check table on previous page for resitivity).

$P = \frac{V^2}{R}$

$R = \frac{V^2}{P}$

$= \frac{(240)^2}{750}$

$= 76.8 \Omega$ (3s.f)

$\rho = 100 \times 10^{-8} \Omega m$

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

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

$= \frac{76.8 \times 1.0 \times 10^{-3} \times 0.05 \times 10^{-3}}{100 \times 10^{-8}}$

$= 3.84 m$ (3s.f)

Worked Example 6.2

A certain electric hotplate, designed to operate on a 250 V supply, has two coils of nichrome wire. Each-coil consists of 16 m of wire of cross-sectional area 0.20 mm^2. For one of the coils calculate

(a) its resistance,

(b) the power dissipation when a 250 V supply is connected across the coil, assuming its resistance does not change with temperature,

(c) the cost of running it for 5 hours if electricity costs \$0.17 per kWh.

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

$= \frac{100\times10^{-8}\times16}{0.2\times10^{-6}}$

$= 80\ \Omega$

b) $P = \frac{V^2}{R}$

$= \frac{(250)^2}{80}$

$= 781\ W$

c) $1\ kWh \rightarrow \$0.17$

$E = 0.781\times5$

$= 3.91\ kWh$

$Cost = 3.906\times0.17$

$= \$0.66\ (2 d.p)$

7 Sources of Electromotive Force

In this section, students are required to:

(a) define e.m.f. in terms of the energy transferred by a source in driving unit charge round a complete circuit.

(b) distinguish between e.m.f. and p.d. in terms of energy considerations.

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

- The circulation of an electric current leads to the continual dissipation of energy throughout the circuit in the form of heat as well as other forms of energy. All this energy must be continuously supplied by the battery, dynamo etc that maintains the flow of current. Or put another way, these devices are able to maintain a potential difference between the two points to which they are attached.
- Such devices in which electrical energy must have been converted from chemical, mechanical or some other forms of energy internally are called sources or seats of **electromotive force** (e.m.f., E).

5 Resistivity

In this section, students are required to:

(a) recall and solve problems using the equation $R = \rho l / A$.

- Experimentally, it is found that the resistance R of a conductor at a given temperature is
  (i) proportional to its length, l
  (ii) inversely proportional to its cross-sectional area A

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

- Hence,

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

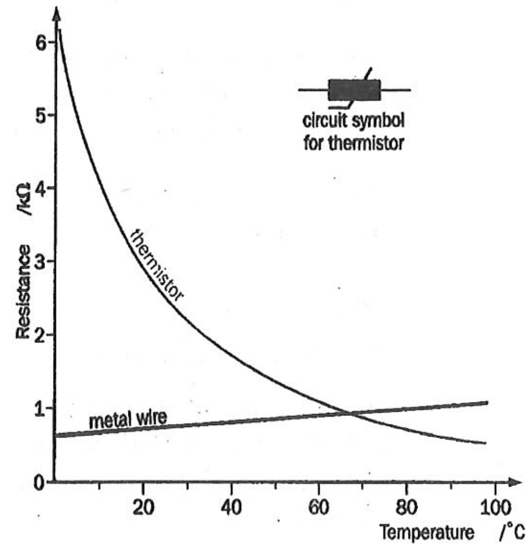
where ρ is a physical constant of the material called its **resistivity**.

- The unit of resistivity is ohm meter (Ωm).
- Resistivity enables comparisons to be made between the conducting ability of different materials. A good electrical conductor has low resistivity and vice-versa. The resistivity for a selection of different materials is given in the table below

	SUBSTANCE	RESISTIVITY AT 25 °C / Ωm	USES
Conductors			
metals	copper	1.72×10^{-8}	connecting wires
	gold	2.42×10^{-8}	microchip contacts
	aluminium	2.82×10^{-8}	power cables
	tungsten	5.51×10^{-8}	light-bulb filaments
alloys	steel	20×10^{-8}	
	constantan	49×10^{-8}	standard resistors
	nichrome	100×10^{-8}	heating elements
Semiconductors			
	carbon	3.5×10^{-5}	resistors
	germanium	0.60	transistors
	silicon	2300	transistors, chips
Insulators			
	glass	$\approx10^{13}$	power grid insulators
	polythene	$\approx10^{14}$	wire insulation

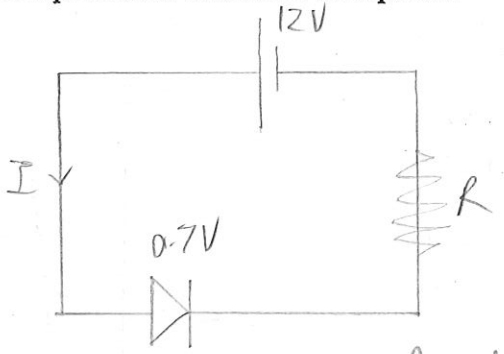
(d) **Thermistor**

- The resistance of many semiconducting materials decreases as their temperature rises. These materials have a negative temperature coefficient of resistance (NTC).
- The **thermistor** is an important semiconducting component. On the graph, the resistance of an NTC thermistor is plotted against temperature. The change in resistance of a metal wire is also shown.
- Earlier we discussed why the resistance of metals increases with temperature. Why do semi-conductors behave differently?
  - In semiconductors, the number of free electrons is small compared to that in metals. Thus, at low temperatures it is a poor conductor.
  - As its temperature rises, more and more electrons break free from the atoms and so the semiconductor becomes a better conductor. still poor as $R \approx 1\,k\Omega$



Worked Example 4.2

An LED (Light Emitting Diode) has been mounted on the dashboard of a car and is to be used as an indicator for the car alarm. The car battery 12 V and the LED requires 10 mA to run correctly. What value of protective resistance is required?



Voltage (p.d) across $R = 12 - 0.7V$

$= 11.3V$

Current through $R = 10 \times 10^{-3} A$

$R = \dfrac{11.3}{10 \times 10^{-3}}$

$= 1130\,\Omega$

Concept Test 2

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Concept Test 3

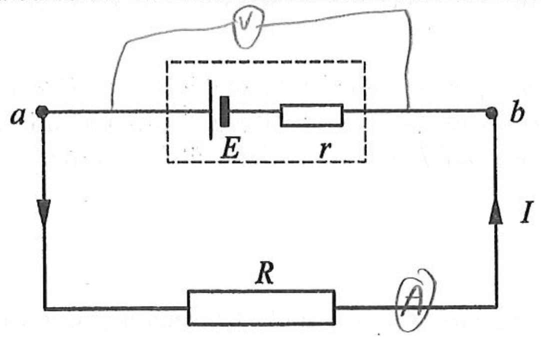
E.m.f. of a source is defined as the amount of energy converted from other forms to electrical energy **when the source drives a** unit charge **round a complete circuit.**

- In equation form it is identical to potential difference.

$$E = \frac{W}{Q}$$

and the SI unit for e.m.f. is also the volt (V).

- Though both potential difference and e.m.f. are W per unit charge, W for emf is the energy converted to electrical from other forms whereas W for p.d. is the energy converted from electrical energy to other forms.
- In practice, not all electrical energy generated is available to the external load because the source of e.m.f. has **internal resistance.** Some energy is lost as heat within the source itself due to this internal resistance.
- Hence the **terminal p.d.** of the source (i.e. the p.d. between its terminals) is smaller than its e.m.f.
- Consider a circuit in which a battery of e.m.f. E and internal resistance r is connected to an external resistor R so that a current I flows in the circuit as shown below.



(i) At the source, electrical energy is generated from chemical energy.

Electrical power supplied by the above source, $P_S = EI$

At the internal resistance (r), electrical power dissipated as heat, $P_r = I^2 r$

At the external load (R), electrical power dissipated as heat, $P_R = I^2 R$

By conservation of energy,

the rate of energy supplied by the source = the rate of heat loss through r and R.

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

Hence, $E = Ir + IR$

$E - Ir = IR$

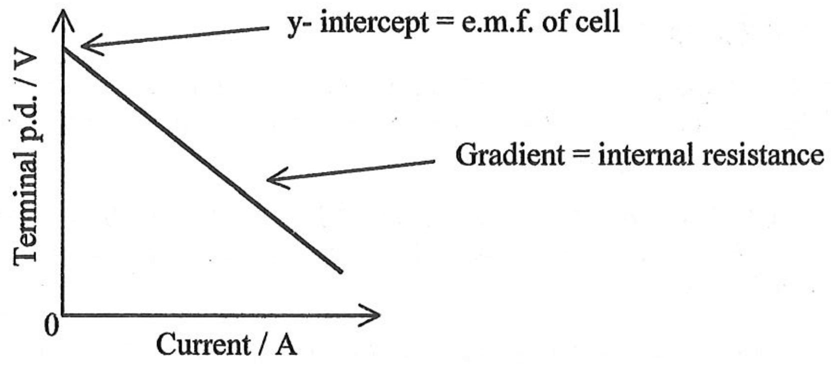
(ii) Terminal p.d.

V_{ab} is called the *terminal* potential difference (i.e. the p.d. across the terminals of the battery). In the above circuit it is equal to the potential difference across the load (or external resistance R), V_R.

Hence $\quad V_{ab} = V_R = IR$

Or equivalently, $\quad V_{ab} = E - Ir$

(iii) The graph of Terminal p.d. vs current is given as follows:



□ **For zero current** there is no p.d. across the internal resistance, so the Terminal p.d. is equal to its e.m.f. when no current is supplied. Therefore, the intercept on the Terminal p.d. axis gives the cell's e.m.f.

□ **For current *I*** the lost p.d. is equal to Ir, so the Terminal p.d. equals $E - Ir$. Ir is represented on the graph by the drop of the Terminal p.d. from the intercept on the vertical axis. The gradient represents the lost p.d./ current, which equals internal resistance r.

Worked Example 7.1

A battery is connected to a variable resistor and a voltmeter is connected across its terminals. When the variable resistor has 6.0 Ω resistance, the voltmeter reading is 4.0 V. When the resistance is 10 Ω the voltmeter reading is 4.4 V. Find the e.m.f. and the internal resistance of the battery.

When $R = 6.0\,\Omega$: $V_{ab} = 4.0\,V$, $I = \frac{4.0}{6.0} = 0.67\,A$

When $R = 10.0\,\Omega$: $V_{ab} = 4.4\,V$, $I = \frac{4.4}{10} = 0.44\,A$

$V_{ab} = E - Ir$

$4.0 = E - 0.67r$ —— (1)

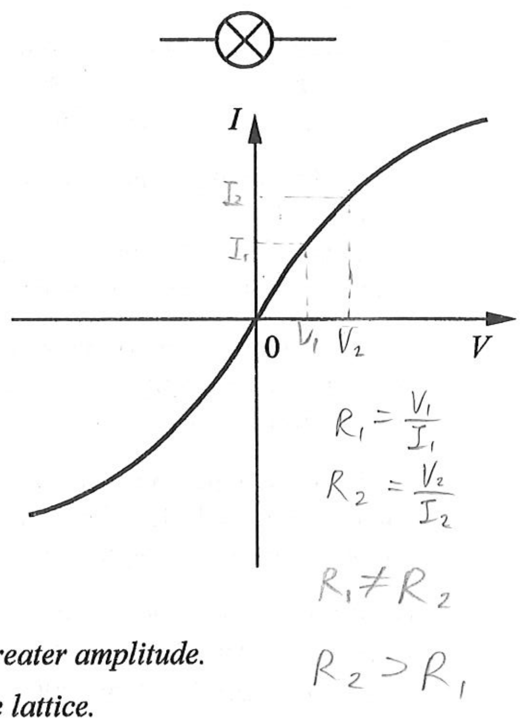
$4.4 = E - 0.44r$ —— (2)

(2)−(1): $0.4 = 0.23r$

$r = 1.74\,\Omega$

$E = 5.17\,V$

(b) **A Filament Lamp**

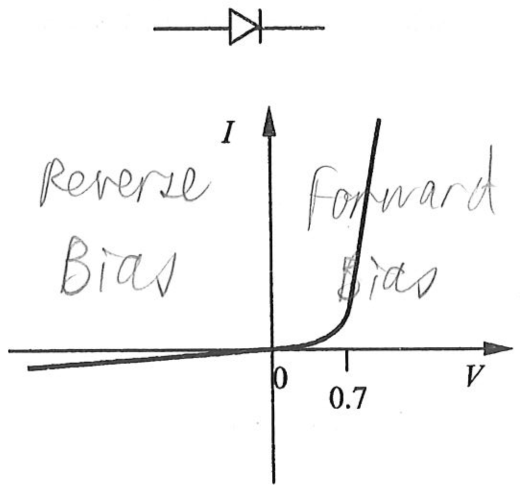


- The **filament lamp** is an example of a non-ohmic device and its *I-V* characteristic is as shown.
- The *I-V* characteristic graph becomes less and less steep as the current increases from zero. So the value of V/I increases as the current increases.
- As the current increases, the metal filament gets hotter and the resistance of the lamp rises.

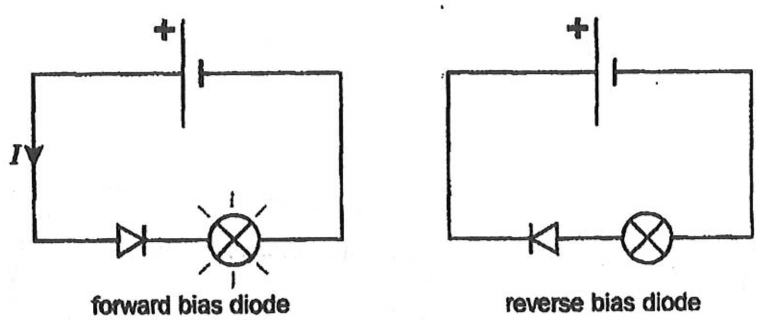
Do you know why?

- *Metals contain large numbers of free electrons.*
- *As these electrons move through the metal lattice they collide with the vibrating metal ions. The collisions oppose the flow of electrons and so the metal has resistance.*
- *As the metal becomes hotter, the ions vibrate faster, with greater amplitude.*
- *It is thus more difficult for the electrons to pass through the lattice.*
- *Hence, the resistance of the metal has increased.*

(c) **A Diode**



- The graphs for the wire and the lamp are symmetrical. The *I-V* characteristic looks the same, regardless of the direction of the current. The **semiconductor diode,** however, behaves differently.
- There is almost no current when the voltage is applied in the reverse direction: **the reverse diode has a very high resistance.**
- In the forward direction, the current increases very rapidly when the voltage rises above about 0.7 V: **the forward diode has a very low resistance** (above 0.7 V)
- The circuit symbol shows the direction of conventional current when the diode conducts. The diode conducts only when it is **forward-biased.** When the diode is **reverse-biased** there is no current (less than one mA).

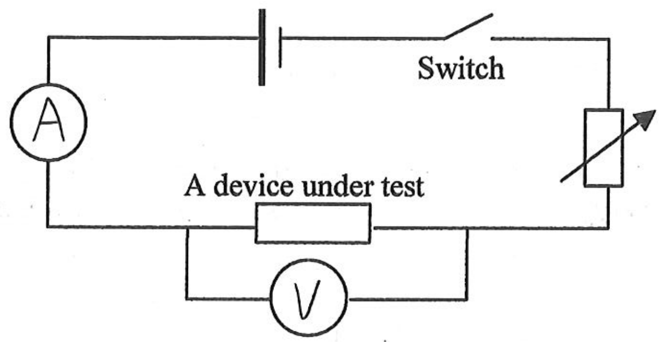


- Ohm investigated how the current, I in a given metal varied with the potential difference, V across it and found that I was proportional to V for many conductors.
- **Ohm's law** for these conductors can be stated as:

> **Under constant physical conditions (i.e. temperature, mechanical stress, etc.) the <u>steady current</u> flowing through a metallic conductor is** directly proportional **to the <u>potential difference</u> between its ends.**

- The circuit below is used to investigate the resistance.

Assume R of A is 0

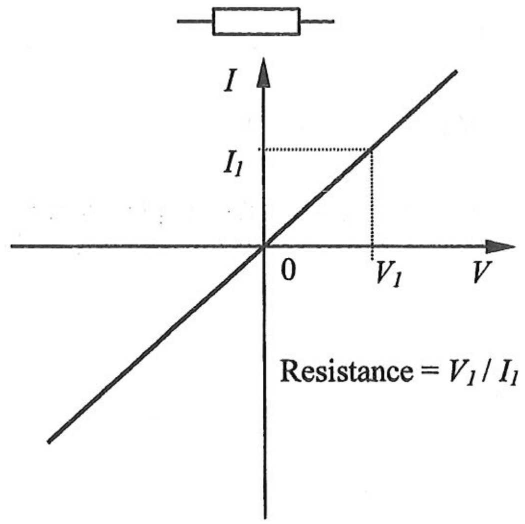


Assume V has ∞ R

I-V Characteristics of Different Circuit Components

(a) **<u>A Length of Wire (Metallic Conductor)</u>**

- The *I-V* characteristic graph is a **straight line through the <u>origin</u>.**
- That is, I is directly proportional to V. If V is doubled, I is doubled too. The ratio V/I and thus resistance is a constant, showing that wire is an **<u>ohmic conductor</u>**.
- An ohmic conductor has a constant resistance independent of the current that is passing through it.



satisfies Ohm Law
$V \propto I$
i.e. straight line passing through origin

Output Power and Maximum power theorem (Optional Reading)

- Using the same circuit, we want to determine the value of R that will result in a maximum power delivered to the load (or power output) P_{out}.
- First, we need to derive an expression for P_{out} in terms of E, r and R.
- Now, $P_{out} = I^2R$
- Since $E = I(r + R)$, eliminating I^2 we have $P_{out} = \dfrac{RE^2}{(r+R)^2}$
- To find maximum P_{out}, we let $\dfrac{dP_{out}}{dR} = 0$, and we obtain: $R = r$
- Hence,

  A given source of e.m.f. delivers the maximum amount of power to a load when the resistance of the load is equal to the internal resistance of the source.

  That is, P_{out} is maximum when $R = r$.
- This is known as the maximum power theorem.

<u>Worked Example 7.2</u>

A cell has e.m.f. 1.5 V and internal resistance 0.5 Ω. Calculate the power delivered when the cell is connected to an external 2.5 Ω resistor. What is the value of the external resistance if the power delivered is to have a maximum value?

<u>Solution</u>

Given: internal resistance, $r = 0.5\Omega$
external resistance, $R = 2.5\Omega$
e.m.f. $= 1.5V$

Total resistance in the circuit $= 2.5 + 0.5 = 3.0\ \Omega$

Current $I = \dfrac{1.5}{(3.0)} = 0.5$ A

Power delivered to the 2.5Ω external resistor, $P_{out} = I^2R = (0.5)^2 \times 2.5 = 0.625$ W

According to the maximum power theorem, P_{out} will be maximum when $R = 0.5\ \Omega$

Worked Example 6.2

A certain electric hotplate, designed to operate on a 250 V supply, has two coils of nichrome wire. Each-coil consists of 16 m of wire of cross-sectional area 0.20 mm^2. For one of the coils calculate

(a) its resistance,

(b) the power dissipation when a 250 V supply is connected across the coil, assuming its resistance does not change with temperature,

(c) the cost of running it for 5 hours if electricity costs $0.17 per kWh.

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

$= \frac{100 \times 10^{-8} \times 16}{0.2 \times 10^{-6}}$

$= 80\ \Omega$

b) $P = \frac{V^2}{R}$

$= \frac{(250)^2}{80}$

$= 781\ W$

c) 1 kWh → $0.17

$E = 0.781 \times 5$

$= 3.91\ kWh$

Cost = 3.906 × 0.17

= $0.66 (2d.p)

7 Sources of Electromotive Force

In this section, students are required to:

(a) define e.m.f. in terms of the energy transferred by a source in driving unit charge round a complete circuit.

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5 Resistivity

In this section, students are required to:

(a) recall and solve problems using the equation $R = \rho l / A$.

- Experimentally, it is found that the resistance *R* of a conductor at a given temperature is
  (i) proportional to its length, *l*
  (ii) inversely proportional to its cross-sectional area *A*

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

- Hence,

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

where ρ is a physical constant of the material called its **resistivity**.

- The unit of resistivity is ohm meter (Ωm).
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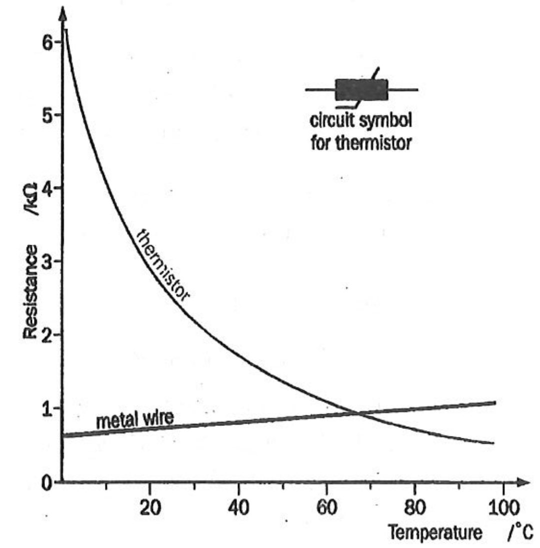
(d) **Thermistor**

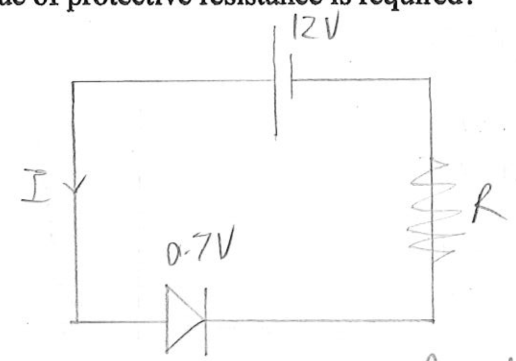
- The resistance of many semiconducting materials decreases as their temperature rises. These materials have a negative temperature coefficient of resistance (NTC).
- The **thermistor** is an important semiconducting component. On the graph, the resistance of an NTC thermistor is plotted against temperature. The change in resistance of a metal wire is also shown.
- Earlier we discussed why the resistance of metals increases with temperature. Why do semi-conductors behave differently?



  - In semiconductors, the number of free electrons is small compared to that in metals. Thus, at low temperatures it is a poor conductor.
  - As its temperature rises, more and more electrons break free from the atoms and so the semiconductor becomes a better conductor. still poor as $R \approx 1\,k\Omega$

Worked Example 4.2

An LED (Light Emitting Diode) has been mounted on the dashboard of a car and is to be used as an indicator for the car alarm. The car battery 12 V and the LED requires 10 mA to run correctly. What value of protective resistance is required?



Voltage (p.d) across $R = 12 - 0.7\,V$
$= 11.3\,V$

Current through $R = 10 \times 10^{-3}\,A$

$$R = \frac{11.3}{10 \times 10^{-3}}$$

$$= 1130\,\Omega$$

Concept Test 2
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Concept Test 3

E.m.f. of a source is defined as the amount of energy converted from other forms to electrical energy **when the source drives a** unit charge **round a complete circuit.**

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and the SI unit for e.m.f. is also the volt (V).

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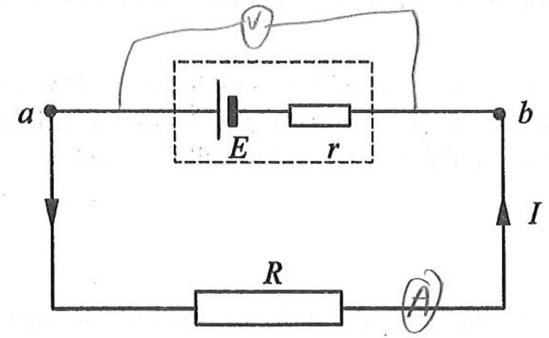
- In practice, not all electrical energy generated is available to the external load because the source of e.m.f. has **internal resistance.** Some energy is lost as heat within the source itself due to this internal resistance.
- Hence the **terminal p.d.** of the source (i.e. the p.d. between its terminals) is smaller than its e.m.f.
- Consider a circuit in which a battery of e.m.f. E and internal resistance r is connected to an external resistor R so that a current I flows in the circuit as shown below.



(i) At the source, electrical energy is generated from chemical energy.

Electrical power supplied by the above source, $P_S = EI$

At the internal resistance (r), electrical power dissipated as heat, $P_r = I^2 r$

At the external load (R), electrical power dissipated as heat, $P_R = I^2 R$

By conservation of energy,

the rate of energy supplied by the source = the rate of heat loss through r and R.

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

Hence,

$$E = Ir + IR$$

$$E - Ir = IR$$

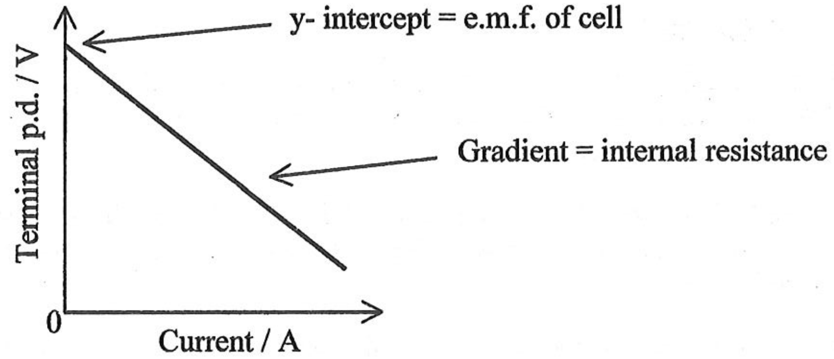
(ii) Terminal p.d.

V_{ab} is called the *terminal* potential difference (i.e. the p.d. across the terminals of the battery). In the above circuit it is equal to the potential difference across the load (or external resistance R), V_R.

Hence $$V_{ab} = V_R = IR$$

Or equivalently, $$V_{ab} = E - Ir$$

(iii) The graph of Terminal p.d. vs current is given as follows:



- **For zero current** there is no p.d. across the internal resistance, so the Terminal p.d. is equal to its e.m.f. when no current is supplied. Therefore, the intercept on the Terminal p.d. axis gives the cell's e.m.f.
- **For current I** the lost p.d. is equal to Ir, so the Terminal p.d. equals $E - Ir$. Ir is represented on the graph by the drop of the Terminal p.d. from the intercept on the vertical axis. The gradient represents the lost p.d./ current, which equals internal resistance r.

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When $R = 6.0\ \Omega$: $V_{ab} = 4.0\text{V}$, $I = \frac{4.0}{6.0} = 0.67\text{A}$

When $R = 10.0\ \Omega$: $V_{ab} = 4.4\text{V}$, $I = \frac{4.4}{10} = 0.44\text{A}$

$V_{ab} = E - Ir$

$4.0 = E - 0.67r$ —— (1)

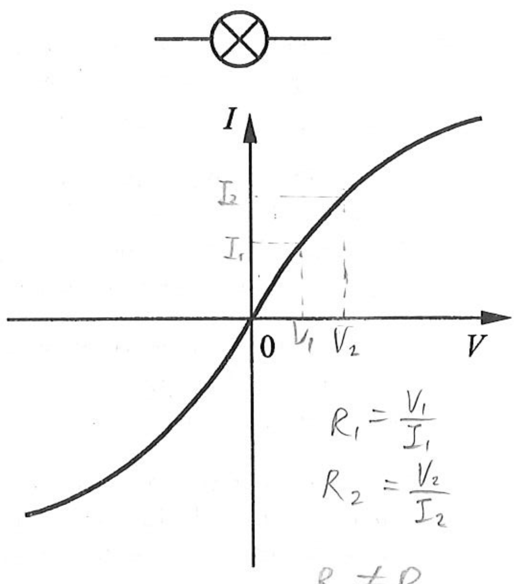
$4.4 = E - 0.44r$ —— (2)

(2) − (1): $0.4 = 0.23r$

$r = 1.74\ \Omega$

$E = 5.17\text{V}$

(b) **A Filament Lamp**



$R_1 = \frac{V_1}{I_1}$

$R_2 = \frac{V_2}{I_2}$

$R_1 \neq R_2$

$R_2 > R_1$

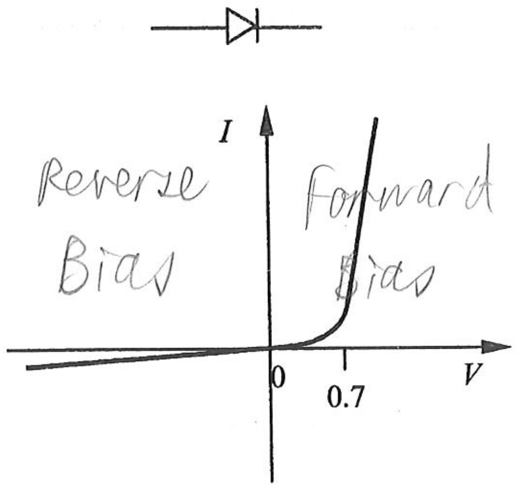
- The **filament lamp** is an example of a non-ohmic device and its *I-V* characteristic is as shown.
- The *I-V* characteristic graph becomes less and less steep as the current increases from zero. So the value of *V/I* increases as the current increases.
- As the current increases, the metal filament gets hotter and the resistance of the lamp rises.

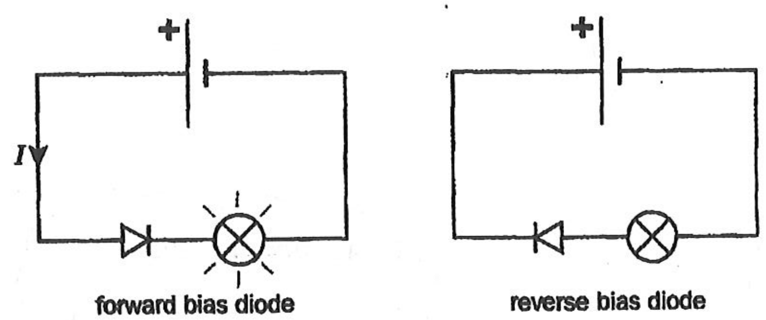
Do you know why?

- *Metals contain large numbers of free electrons.*
- *As these electrons move through the metal lattice they collide with the vibrating metal ions. The collisions oppose the flow of electrons and so the metal has resistance.*
- *As the metal becomes hotter, the ions vibrate faster, with greater amplitude.*
- *It is thus more difficult for the electrons to pass through the lattice.*
- *Hence, the resistance of the metal has increased.*

(c) **A Diode**

- The graphs for the wire and the lamp are symmetrical. The *I-V* characteristic looks the same, regardless of the direction of the current. The **semiconductor diode,** however, behaves differently.
- There is almost no current when the voltage is applied in the reverse direction: **the reverse diode has a very high resistance.**
- In the forward direction, the current increases very rapidly when the voltage rises above about 0.7 V: **the forward diode has a very low resistance** (above 0.7 V)
- The circuit symbol shows the direction of conventional current when the diode conducts. The diode conducts only when it is **forward-biased.** When the diode is **reverse-biased** there is no current (less than one mA).



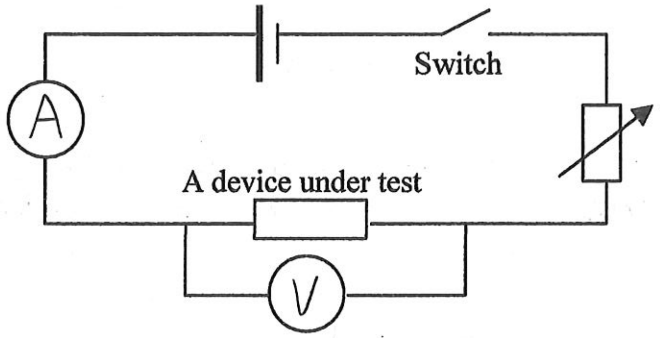


- Ohm investigated how the current, I in a given metal varied with the potential difference, V across it and found that I was proportional to V for many conductors.
- **Ohm's law** for these conductors can be stated as:

Under constant physical conditions (i.e. temperature, mechanical stress, etc.) the steady current flowing through a metallic conductor is directly proportional **to the potential difference between its ends.**

- The circuit below is used to investigate the resistance.

Assume R of A is 0.

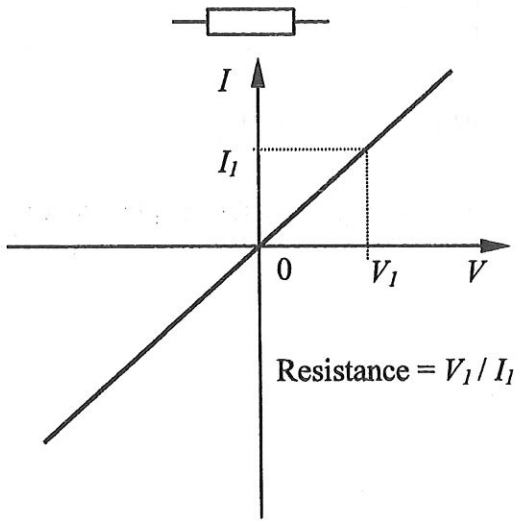


Assume V has ∞ R

I-V Characteristics of Different Circuit Components

(a) **A Length of Wire (Metallic Conductor)**

- The *I-V* characteristic graph is a **straight line through the origin.**
- That is, I is directly proportional to V. If V is doubled, I is doubled too. The ratio V/I and thus resistance is a constant, showing that wire is an **ohmic conductor**.
- An ohmic conductor has a constant resistance independent of the current that is passing through it.



satisfies Ohm Law

$V \propto I$

i.e. straight line passing through origin

Output Power and Maximum power theorem (Optional Reading)

- Using the same circuit, we want to determine the value of R that will result in a maximum power delivered to the load (or power output) P_{out}.
- First, we need to derive an expression for P_{out} in terms of E, r and R.
- Now, $P_{out} = I^2R$
- Since $E = I(r + R)$, eliminating I^2 we have $P_{out} = \dfrac{RE^2}{(r+R)^2}$
- To find maximum P_{out}, we let $\dfrac{dP_{out}}{dR} = 0$, and we obtain: $R = r$
- Hence,

  A given source of e.m.f. delivers the maximum amount of power to a load when the resistance of the load is equal to the internal resistance of the source.

  That is, P_{out} is maximum when $R = r$.
- This is known as the maximum power theorem.

Worked Example 7.2

A cell has e.m.f. 1.5 V and internal resistance 0.5 Ω. Calculate the power delivered when the cell is connected to an external 2.5 Ω resistor. What is the value of the external resistance if the power delivered is to have a maximum value?

Solution

Given: internal resistance, r = 0.5Ω
external resistance, R = 2.5Ω
e.m.f. = 1.5V

Total resistance in the circuit = 2.5 + 0.5 = 3.0 Ω

Current $I = \dfrac{1.5}{(3.0)} = 0.5$ A

Power delivered to the 2.5Ω external resistor, $P_{out} = I^2R = (0.5)^2 \times 2.5 = 0.625$ W

According to the maximum power theorem, P_{out} will be maximum when R = 0.5 Ω

Worked Example 7.3

A copper wire of length 16 m has a resistance of 0.85 Ω. The wire is connected across the terminals of a battery of e.m.f. 1.5 V and internal resistance 0.40 Ω.

(a) Calculate
 (i) the potential difference across the wire,
 (ii) the power dissipated in it.

(b) In an experiment, the length of this wire connected across the terminals of the battery is gradually reduced from 16 m to 0.25 m.
 (i) Sketch a graph to show how the power dissipated in the wire varies with the connected length. On the graph, label the point corresponding to the condition at which the power dissipated in the wire is a maximum.
 (ii) Calculate the length of the wire when the power dissipated in the wire is a maximum.
 (iii) Calculate the maximum power dissipated in the wire.

Solution

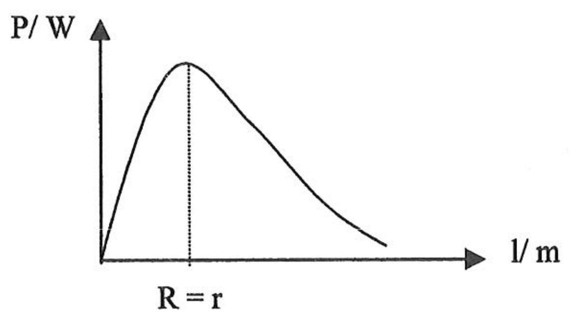
(a) (i) Total resistance in the circuit = 0.85 + 0.40 = 1.25 Ω

$$I = \frac{1.5}{(1.25)} = 1.2 \text{ A}$$

p.d. across wire = IR = 1.2 x 0.85 = 1.02 V

(ii) Power dissipated by wire = $I^2R = (1.2)^2 (0.85) = 1.22$ W

(b) (i)



(ii) Power dissipated is max when R = r = 0.40 Ω

$$R \propto l \Rightarrow \frac{l}{16} = \frac{0.40}{0.85}, \text{ hence } l = 7.53 \text{ m}$$

$$\text{(iii)Max power dissipated in wire} = I^2R = \left(\frac{E}{0.4+0.4}\right)^2 (0.4) = 1.41 \text{ W}$$

4 Resistance

In this section, students are required to:

(a) define resistance and the ohm.

(b) recall and use $V = IR$..

(c) sketch and explain the *I-V* characteristics of a metallic conductor at constant temperature, a semi-conductor diode and a filament lamp.

(d) sketch the temperature characteristic of a thermistor.

(e) state Ohm's law.

- Resistance is the opposition to the flow of charge.
 current

The resistance R of a conductor is defined as the ratio **of the** potential difference**, V across it to the** current**, I through it.**

- That is, $\boxed{R = \frac{V}{I}}$

- The SI unit of resistance is the ohm, Ω.

One ohm is defined as the resistance of a conductor when a current of <u>one ampere</u> passes through it when the potential difference across it is <u>one volt</u>.

Worked Example 4.1

(a) What p.d. must be applied to a 16 Ω resistor to drive a current of 0.25 A through it?
(b) What is the resistance of a wire that requires of p.d. of 6.0 V to drive a current of 0.20 A?

$R = \frac{V}{I}$
$V = IR$
$= 4.0V$

$R = \frac{V}{I}$
$= 30 \Omega$

Worked Example 3.1

A lamp has a p.d. of 12 V across it. Calculate how much electrical energy is transferred when:
(a) a charge of 400 C passes through it,
(b) a current of 2.5 A passes through it for 30 s.

$W = QV$
$= 400 \times 12$
$= 4800\ J$
$= 4.8\ kJ$

$W = Pt$
$= IVt$
$= 2.5 \times 12 \times 30$
$= 900\ J$

Worked Example 3.2

An immersion heater is rated at 3000 W and is switched on for 2000 s. During this time a charge of 25000 C is supplied to the heater. Find the potential difference across the heater.

$P = IV$
$P = \frac{Q}{t}V$
$V = \frac{Pt}{Q}$

$V = \frac{3000 \times 2000}{25000}$
$= 240V$

Worked Example 3.3 (the Electron Volt)

To quantify energy associated with subatomic particles, an alternative unit of energy called the electron volt is used. One electron volt (or 1 eV) is the amount of energy acquired when an electron is accelerated through a potential difference of 1 volt. Express 1 eV in terms of joules. (charge on an electron = 1.6×10^{-19} C).

$1eV = 1 \times 1.6 \times 10^{-19}$
$= 1.6 \times 10^{-19} J$

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2. Understanding Physics for Advanced Level, Jim Breithaupt 4th edn. P444, 530 BRE
3. Advanced Physics, Steve Adams & Jonathan Allday , P128, 530 ADA, Oxford

Websites

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http://www.explorescience.com/activities/Activity_page.cfm?Activity_ID=59

LDR 

light, R ↓
dark, R ↑

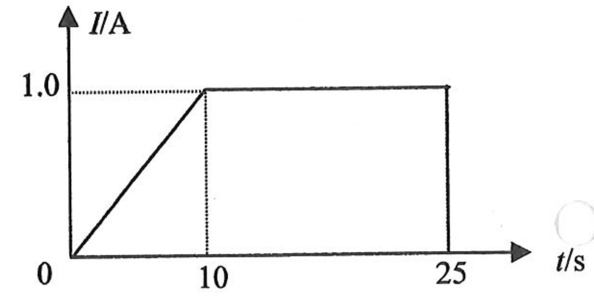
Thermistor
temp ↑, R ↓
temp ↓, R ↑

Current of Electricity Tutorial

Self-Attempt

1. (a) Copper has a density of 8930 kgm^{-3}. Calculate the mass of a copper wire that has a cross-section of 1.0 mm^2 and is 10 cm long.
(b) Each copper atom has the mass of approximately 64 protons (mass of one proton = 1.67 x 10^{-27} kg). How many copper atoms are there in the wire? If each copper atom has 64 electrons, how many electrons are there in the wire? 29
(c) The copper wire carries a current of 1 A. How many electrons per second are moving from one end of the wire to the other? What fraction of the total number of electrons in moving? (electronic charge = -1.6 x 10^{-19} C)

2. The variation of current through a point with time is shown in the diagram on the right. Find the total charge that flows through that point from 0 to 25s. (*Hint:* $Q = \int I dt$)



3. A light bulb is marked 240 V, 60 W. It is switched on for 10 000 s. Assuming that the bulb is being used correctly, find:
(a) the total energy converted by the bulb from electrical energy;
(b) the total charge supplied to the bulb (*Hint : use definition of p.d.*);
(c) the current.

4. A light-dependent resistor (LDR) has a p.d. of 6.0 V across it. When it is not illuminated a current of 0.87 mA flows through it, but when it is illuminated the current increases to 53 mA. Find the resistance of the LDR in both cases.

5. A torchbulb X is connected in series with a variable resistor and an 18 V battery of negligible internal resistance. The variable resistor is adjusted until torchbulb operates at its normal rating, which is 12 V and 24 W.
(a) Calculate the current in X and its resistance.
(b) Calculate the p.d. and the power dissipation in the variable resistor.

6. A diode D conducts only if the p.d. across its terminals exceeds 0.6 V in the forward direction. The diode is connected in its forward direction in series with a 1.5 V cell and a 2.2 kΩ resistor.
(a) Calculate the p.d. across resistor and current.
(b) A 1.0 kΩ resistor is connected in parallel with the 2.2 kΩ resistor. Calculate the current through the 2.2 k Ω resistor now.
(c) The current through the diode should not exceed 3 mA. Calculate the least resistance of a resistor to be connected in series with the diode and the 1.5 V cell.

7. A rectangular carbon block has dimensions 1.0 cm × 1.0 cm × 50.0 cm. When a potential difference of 1.0 V was applied between its two square ends, the current flowing through it was measured to be 5.7 A.
(a) What is the resistance of the carbon block between its two square ends,
(b) What is the resistivity of carbon?

3 Potential Difference

In this section, students are required to:

(a) define potential difference and the volt.

(b) recall and use $V = W/Q$.

- In the earlier topic *Electric Fields*, we have come across the quantity electric potential difference. This term is used in the context of electric field and is defined as the work done in bringing unit charge from one point of the field to another.
- In this topic we are dealing with electrical circuits, which are basically used to transfer energy from one place (usually the battery or mains) to another (motor, lamp, speaker, resistor, etc). Recall that whenever work is done, there is an energy conversion and in this case from electrical to other forms.
- Hence, potential difference between two points in a circuit is defined as follows:

The potential difference between two points in a circuit is the amount of electrical energy **converted to other forms of energy when** unit charge **passes from one point to another.**

- In equation form this becomes

$$\boxed{V = \frac{W}{Q}}$$

where W is the energy converted from electrical to other forms when a charge of Q passes from one point to another.

- The SI unit for potential difference is the volt (V).

One volt is defined as the potential difference between 2 points in a circuit in which one joule of energy (electrical) **is converted when a charge of** one coulomb **passes from one point to the other.**

- We can consider rate of energy conversion and rate of charge flow instead

Starting from $V = \frac{W}{Q}$ and knowing $P = \frac{W}{t}$ and $I = \frac{Q}{t}$

$$\boxed{V = \frac{P}{I}} \qquad P = IV$$

where P is rate at which the energy converted and I is the current i.e. rate at which charge passes from one point to another.

- If the current is not constant,

$$\boxed{Q = \int I\,dt}$$

Average $I = \frac{Q}{T}$

$= \frac{1}{T}\int_0^T I\,dt$

i.e. the charge can be found from the area beneath the current-time graph.

Worked Example 2.1

A TV tube produces a beam of electrons which strikes the fluorescent screen at the front of the tube. The beam current is 10 mA. How much charge strikes the screen in 10 min?

$Q = It = 10 \times 10^{-3} \times 10 \times 60$

$= 6.0\ C$

Worked Example 2.2

If a lightning strike has an average current of 10 000 A and carries a charge of 20 C to Earth, how long does the strike last for?

$Q = It$

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

$= \frac{20}{10000}$

$= 2.0 \times 10^{-3}\ s$

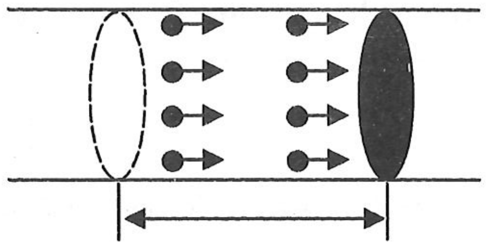
Concept Test 1

TYS Q7 P185

Worked Example 2.3 (Drift velocity)

Consider a cylindrical conductor of cross-sectional area *A*. A potential difference is applied across it such that an electric field is set up in the conductor. The electric field causes the mobile carriers each of charge *q* to move across the conductor with a drift velocity *v*. Given there *n* charge carriers per unit volume in the conductor, express current *I* in terms of *A*, *n*, *v* and *q*.

- In unit time,
- Number of charge carriers that passes through a cross section = nAv
- Amount of charge that passes through the cross section = $qnAv$



- Hence, $\boxed{I = qnAv}$

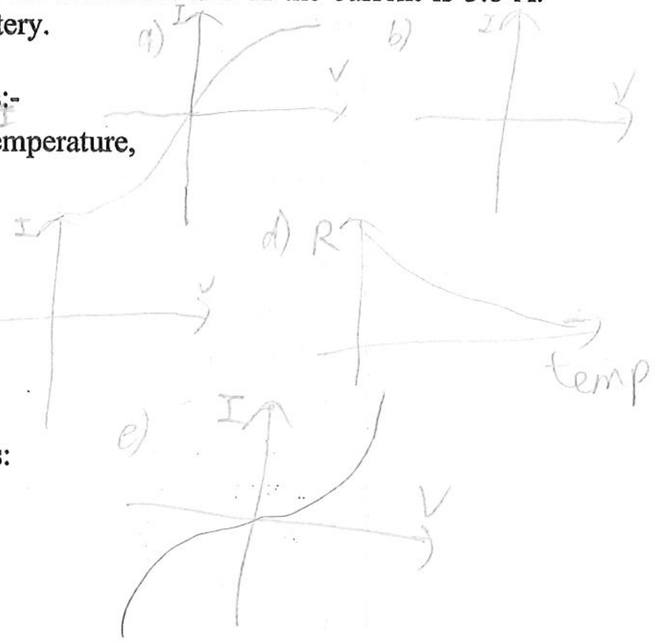
For wire, $I = nAve$

8. A 200 W TV is switched on for 4 hours each day. Calculate, in one month (30 days),
   (a) the energy consumed in J and in kWh,
   (b) the cost of running the TV if electricity costs $0.165 per kWh.

9 The filament of a bulb is to emit 60 W of light energy. If the bulb is 40% efficient at converting electric energy into light, what is its resistance when connected to a 240 V supply? What is its length if its resistvity is 2.0 x 10^{-3} Ωm at its normal operating temperature and it is 0.50 mm thick?

10 A battery is connected in series with a variable resistor and an ammeter. When the resistance of the resistor is 10 Ω the current is 2.0 A. When the resistance is 5 Ω the current is 3.8 A. Find the e.m.f. and the internal resistance of the battery.

11 Sketch the following graphs and explain their shapes:-
   (a) *I-V* characteristic of a copper wire at constant temperature,
   (b) *I-V* characteristic of a semi-conductor diode,
   (c) *I-V* characteristic of a filament lamp,
   (d) temperature characteristic of a thermistor.
   (e) I-V of thermistor



Discussion

12 Distinguish between the following pairs of quantities:
   (a) Charge and Current
   (b) Potential and Potential difference
   (c) Resistance and Resistivity
   (d) Potential difference and Electromotive Force

13 In a tube containing ionized gases, when a p.d. is applied to the two electrodes the current is 0.4 A. In one second, there are 1.25 × 10^{18} electrons moving in one direction across the cross-sectional area of the tube. Calculate the number of positive ions moving across the same cross-sectional area in one second if the charge on each ion is +2*e*. Also, specify the direction of their flow relative to that of the electrons.

14 A solar cell generates a potential difference of 0.10 V when a 500 Ω resistor is connected across it and a potential difference of 0.15 V when a 1000 Ω resistor is substituted. What are
   (a) the internal resistance and
   (b) the e.m.f. of the solar cell?
   (c) The area of the cell is 5.0 cm^2 and the rate per unit area at which it receives light energy is 2.0 mW/cm^2. What is the efficiency of the cell for converting light energy to thermal energy in the 1000 Ω external resistor?

15 A car battery has an e.m.f. of 12.0 V. When a car is started the battery supplies a current of 105 A to the starter motor. The terminal potential difference between the battery terminals drops at this time to 10.8 V due to the internal resistance of the battery.
   (a) Explain briefly what is meant by:
      (i) an e.m.f. of 12.0 V;
      (ii) the internal resistance of the battery.

(b) Calculate the internal resistance of the battery.

(c) The manufacturer warns against short-circuiting the battery.

(i) Calculate the current which would flow if the terminals were to be short-circuited.

(ii) Explain briefly why the manufacturer provides this warning. Justify your explanation with an appropriate calculation.

(d) When completely discharged, the battery can be fully recharged by a current of 2.5 A supplied for 20 hours.

(i) How much charge is stored by the battery?

(ii) For how long could the motor be operated on a fully-charged battery? Assume that the motor could be operated continuously.

16 In a particular household the average use per day of electrical appliances during a 100-day period was as shown in table below.

APPLIANCE	POWER	AVERAGE TIME USED PER DAY
immersion heater	3 kW	2 h
cooker oven	2 kW	1 h
lights	60 W	30 h
lights	100 W	20 h
television	200 W	5 h
refrigerator	200 W	10 h
air conditioner	750 W	10 h
vacuum cleaner	400 W	15 min
washing machine	500 W	30 min
hair drier	1200 W	15 min
iron	800 W	15 min
stereo	40 W	1 h 30 min
various other items	2 kW	1 h

(a) If 1 kW h costs $0.165, find how large a bill will be expected at the end of the 100 days.

(b) What would you recommend as an economy measure?

(c) How can 60 W lights be on for 30 h in one day?

(d) A refrigerator is normally left on all the time. Why is it therefore that the times given in the table are less than 24 h?

Answers:

1 8.93×10^{-4} kg, 8.36×10^{21}, 5.23×10^{23}, 6.2×10^{18}, 1.2×10^{-8} %

2 20 C.

3 (a) 6.0×10^{5} J, (b) 2500 C (c) 0.25 A

4 (a) 6900 Ω, 110 Ω

5 (a) 2A, 6Ω (b) 6V, 12W

6 (a)0.9 V, 0.41 mA (b) 0.41 mA (c) 300Ω

7 (a) 0.175 Ω, 3.5×10^{-5} Ωm

8 (a) 8.6×10^{6}J, 24 kWh (b) $3.96

9 380 Ω, 0.04 m

10 21 V, 0.56Ω

12 6.25×10^{17}

13 416

15 (a) 1000 Ω, (b) 0.30 V, (c) 0.23 %

16 b) 0.0114 Ω (c) (i) 1050 A (d) 1.8×10^{5} C, (iii) 29 min

o What is the effect on the charge on A and B in both situations? What can you conclude from these results?

Same amount of charge on A & B. Flow of negative charges in one direction equivilant to a flow of an equal amount of positive charges in the opposite direction in the same time.

o *Is electric current a vector?*

No. Does not obey the laws of vector addition.

- Under the SI system, electric current is the base electrical quantity and ampere (A) is the base electrical unit. This means all other electrical quantities are defined in terms of electric current and all other units are defined in terms of ampere.

2 Electric Charge

In this section, students are required to:

(a) define charge and the coulomb.

(b) recall and solve problems using the equation $Q = It$.

- As mentioned earlier, electric current is the **base electrical quantity**. Hence, electric charge is defined in terms of electric current.
- Charge is defined as follows:

The charge Q, which flows past a point in time t if there is a constant current I, is the product of current and time **.**

$$\boxed{Q = It}$$

- The unit of charge is the coulomb (C). It is defined in terms of ampere.

One coulomb **is defined as the charge that in one second crosses a section of a circuit in which there is a constant current of** one **ampere.**

1 Electric Current

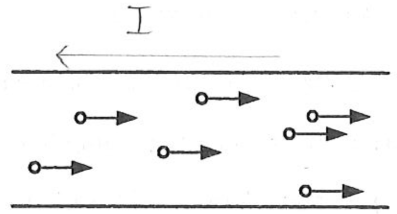
In this section, students are required to:

(a) show an understanding that electric current is the rate of flow of charged particles.

- When there is a flow of charged particles (delocalised electrons, ions, etc), a current is said to flow.
- **Electric current is the rate of flow of** positive charges. The SI unit is ampere (A).
- Usually an arrow is used to indicate the direction of flow of an electric current. The convention is to consider current flow in terms of **positive charges**.

Worked Example 1.1

Upon application of a potential difference, there is a flow of delocalised electrons in a metal conductor as shown in the diagram.
Indicate the direction of current. Why?

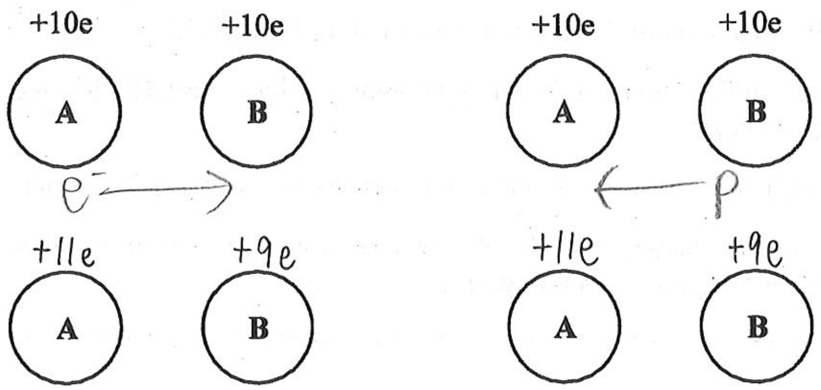


By convention, the direction of current is taken to be the same as the direction of flow of positive charges.

Worked Example 1.2

- Consider two conductors A & B. A and B each has a charge (an excess charge to be exact) of +10*e*.
- Compare two situations :-

an electron is brought from A to B | a proton is brought from B to A

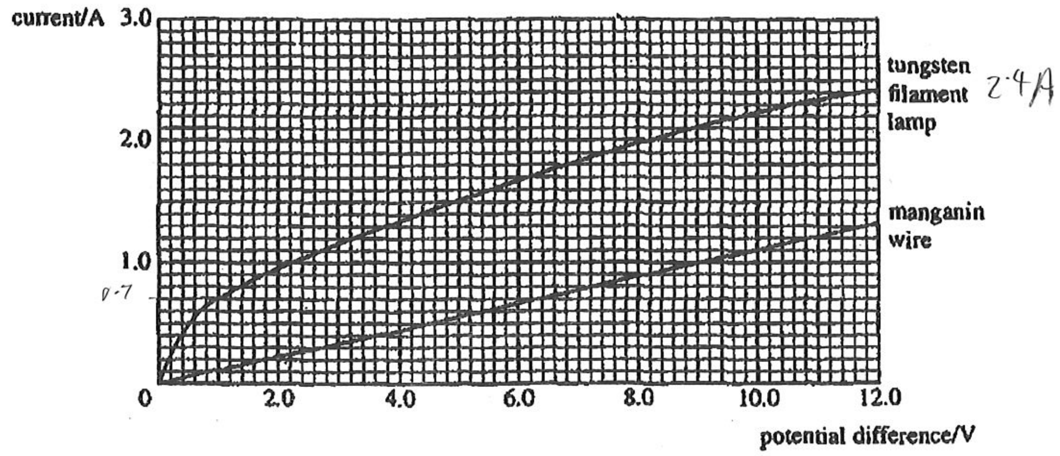


Assignment :

0.049 mm × 1 mm 4.9×10^{-2}
4.9×10^{-5} 1×10^{-3} 4.9×10^{-8}

17 (a) State Ohm's law.

(b) The graph shows how current, *I*, varies with potential difference, *V*, for a manganin wire of length 1.0 m and cross-sectional area 0.049 mm^2, and for a tungsten filament lamp.



(i) Determine the resistance of the tungsten filament
1 when $V = 1.0$ V
2 when $V = 12$ V.

(ii) Explain why these two values are different.

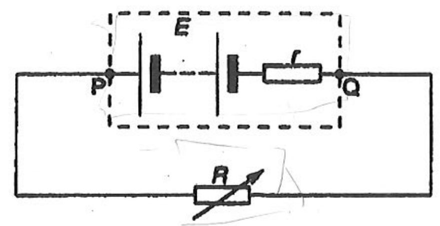
(c) Use the graph in part (b) to show that the resistivity of manganin is approximately 4.5×10^{-7} Ωm.

(d) You are supplied with manganin wire of diameter 0.40 mm and asked to make a heating coil which will dissipate 1.0 kW when connected to a 200 V supply.

(i) Calculate the resistance of the coil.

(ii) Calculate the length of wire which is required.

18 A battery of e.m.f. *E* and internal resistance *r is* connected to a variable external resistor of resistance *R*, as shown.



When $R = 16$ Ω, the current in the circuit is 0.45 A. The circuit is switched on for 1000 s and it is found that during this time, the battery supplies 4050 J of energy to the two resistors.

(a) Calculate

(i) the charge which the battery delivers in 1000 s, 0.45

(ii) the e.m.f. *E* of the battery, 9V

(iii) the potential difference across PQ, the terminals of the battery,

(iv) the internal resistance *r* of the battery.

(b) Describe qualitatively how the resistance *R* should be changed in order to make the potential difference across PQ have a value closer to *E*, the e.m.f. of the battery.

bi) lose a ~~neutron~~ nucleus

bii) ~~stable~~ stable nuclei does not undergo decay. Hence its [conc] will ↑ with time

A

-Chain reaction

-series of nuclear reactions initiated by a single nuclear fission

-fission of a U nucleus produces 2-3 neutrons which are neccessary components to initiate fission in nearby U nucleus

-which would induce fission in 9 other U nuclei & so on

ii) No. of neutrons produced ↑ exponentially

- At final stage, greatest no. of neutron cause fission in whatever U nuclei left

Bi) Range of percentage yield of diff fission product is very large thus a logarithmic scale is neccessary to include all % yield over range of nucleon no.

108 127 152

152

~6.5%

CURRENT OF ELECTRICITY

Content

1 Electric Current
2 Electric Charge
3 Potential Difference
4 Resistance
5 Resistivity
6 Electrical Power
7 Sources of Electromotive Force

Learning Outcomes

At the end of the lesson, you should be able to:

(a) show an understanding that electric current is the rate of flow of charged particles.

(b) define charge and the coulomb.

(c) recall and solve problems using the equation $Q = It$.

(d) define potential difference and the volt.

(e) recall and use $V = W/Q$.

(f) recall and use $P = VI$, $P = I^2R$.

(g) define resistance and the ohm.

(h) recall and use $V = IR$.

(i) sketch and explain the I-V characteristics of a metallic conductor at constant temperature, a semi-conductor diode and a filament lamp.

(j) sketch the temperature characteristic of a thermistor.

(k) state Ohm's law.

(l) recall and solve problems using the equation $R = \rho l / A$.

(m) define e.m.f. in terms of the energy transferred by a source in driving unit charge round a complete circuit.

(n) distinguish between e.m.f. and p.d. in terms of energy considerations.

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