Topic 9 Current of Electricity

Guiding Questions:

- *How does the macroscopic phenomenon of current flow relate to the movement of microscopic charges?*
- *How are current, voltage, and resistance related in an electrical circuit?*
- *What happens to energy in an electrical circuit?*

Content

- Electric current
- Potential difference
- Resistance and resistivity
- Electromotive force

Learning Outcomes

Candidates should be able to:

(a) show an understanding that electric current is the rate of flow of charge

(b) derive and use the equation $I = nAvq$ for a current-carrying conductor, where n is the number density of charge carriers and v is the drift velocity

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

(d) recall and solve problems using the equation $V = W / Q$

(e) recall and solve problems using the equations $P = VI$, $P = I^2R$ and $P = V^2 / R$

(f) define the resistance of a circuit component as the ratio of the potential difference across the component to the current passing through it and solve problems using the equation $V = IR$

(g) sketch and explain the I–V characteristics of various electrical components such as an ohmic resistor, a semiconductor diode, a filament lamp and a negative temperature coefficient (NTC) thermistor

(h) sketch the resistance-temperature characteristic of an NTC thermistor

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

(j) distinguish between electromotive force (e.m.f.) and potential difference (p.d.) using energy considerations

(k) 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.

Introduction

Charge is a property possessed by some (but not all) elementary particles (e.g. electrons, protons). Charge is found as two types, positive and negative, which 'neutralise' one another if brought together in equal quantities. Objects that have an electrical charge exert electrostatic forces on each other.

The SI unit used to measure electrical charge is the **coulomb** (C). Physicists used to think that electrical charge could only be found in whole number multiples of a fundamental amount of charge,

$$e = 1.602192 \times 10^{-19}\ \text{C}.$$

Charge on the proton = $+e$

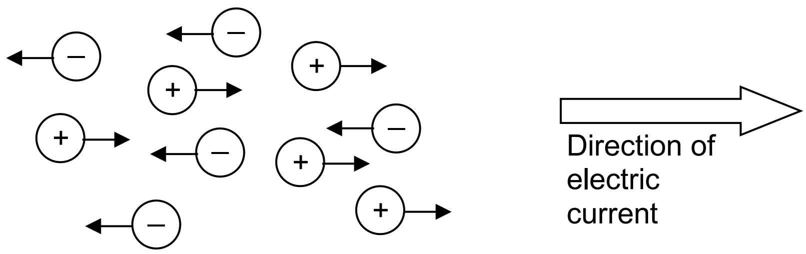
Charge on the electron = $-e$

However, in the late 1960s, small particles called quarks were discovered with electric charge of either $+\frac{2}{3}e$ or $-\frac{1}{3}e$. These, together with $-e$, seem to be the basic quantities of electric charge.

(a) show an understanding that electric current is the rate of flow of charge
(c) recall and solve problems using the equation Q = It

Electric current (SI base unit: *ampere*), consists of *charges in motion* from one region to another. When this motion takes place within a conducting path that forms a closed loop, the path is called an *electric circuit*.

In metals, current is due to the flow of electrons which carry negative charges. It should be noted, however, that the direction of the current is, *by convention*, the direction that positive charges move.



At room temperature, metals such as copper or iron have electrons that are *free to move* within the physical constraints of the material. These free electrons move *randomly in all directions*, somewhat like the molecules of a gas but with much greater speeds (of the order of 10^6 m s^{-1}).

Electric current flowing through a cross-section of a conductor is the rate of flow of charges through it. Hence, the instantaneous current passing through a cross section of the conductor at a given time is given by

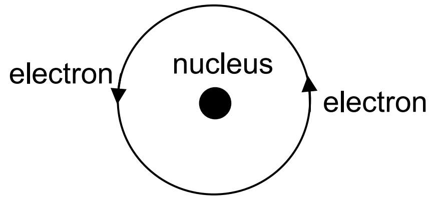
$$I = \frac{dQ}{dt}$$

If the electric current I is steady, then the total amount of charge Q which flows past a point in a time duration t would be given by

$$\boxed{Q = It}$$

Example 1

The diagram on the right shows a model of an atom in which two electrons move round a nucleus in a circular orbit. The electrons complete one full orbit in 1.0×10^{-10} s. What is the current caused by the motion of the electrons in the orbit?

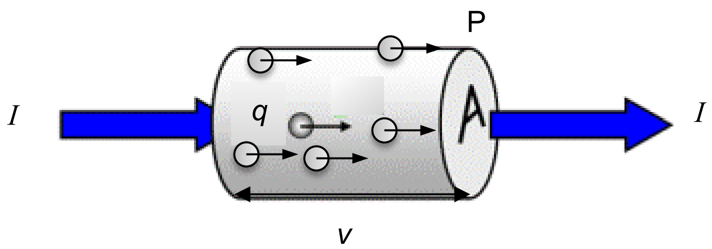


Example 2

A high potential is applied between the electrodes of a discharge tube so that the gas is ionized. Electrons and positive ions move towards the positive and negative electrodes respectively. In each second, 5×10^{18} electrons and 2×10^{18} singly charged positive ions pass a cross-section of the tube. Determine the current flowing in the discharge tube.

(b) *derive and use the equation $I = nAvq$ for a current-carrying conductor, where n is the number density of charge carriers and v is the drift velocity*

The diagram shows a current passing through a cross section of a wire. Each positive charge carrier has charge *q* and there are *n* charge carriers per unit volume. Their average drift velocity is *v*. One section of the wire has been magnified. Its cross-sectional area is *A*.



Current = rate of flow of charge
= (number of charge carriers *per unit time*) × (charge on each carrier)

The number of charge carriers *per unit time* passing a point (P) in the wire is equal to the number contained in a volume of wire with length v.

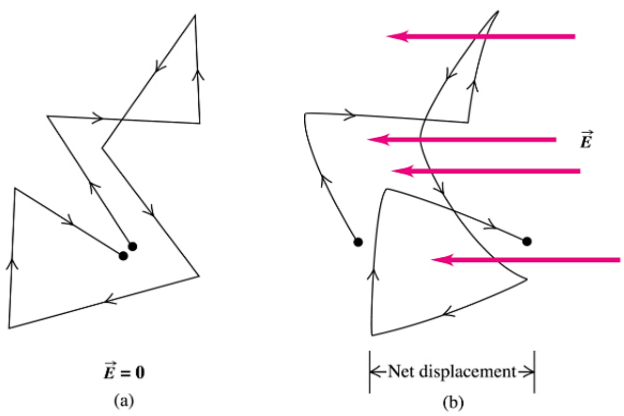
$\therefore$ number of charge carriers per unit time $= nAv$

Thus the current in wire is $\boxed{I = nAvq}$

Note
- The thinner the wire (for the same current) the faster the charge carriers must move.
- If current is increased, the only term that can increase is v.
- For the same length of wire, greater cross-sectional area allows more room for charge carriers, leading to more current.

Drift velocity *v*

Thermal energy makes free charge carriers move about at high speeds (of the order of 10^6 m s^{-1}). The collisions between electrons and metal ions are frequent and random. Thermal motion does not carry the electron any distance along the wire. Under the influence of a potential difference applied across the conductor, the charge carriers gain an additional drift motion that carries them along the conductor (at the order of 10^{-4} m s^{-1}) and as a result, charge is transferred. The direction of this drift is not random, as they are being directed by the field lines from the cell. This is the drift velocity.



Example 3

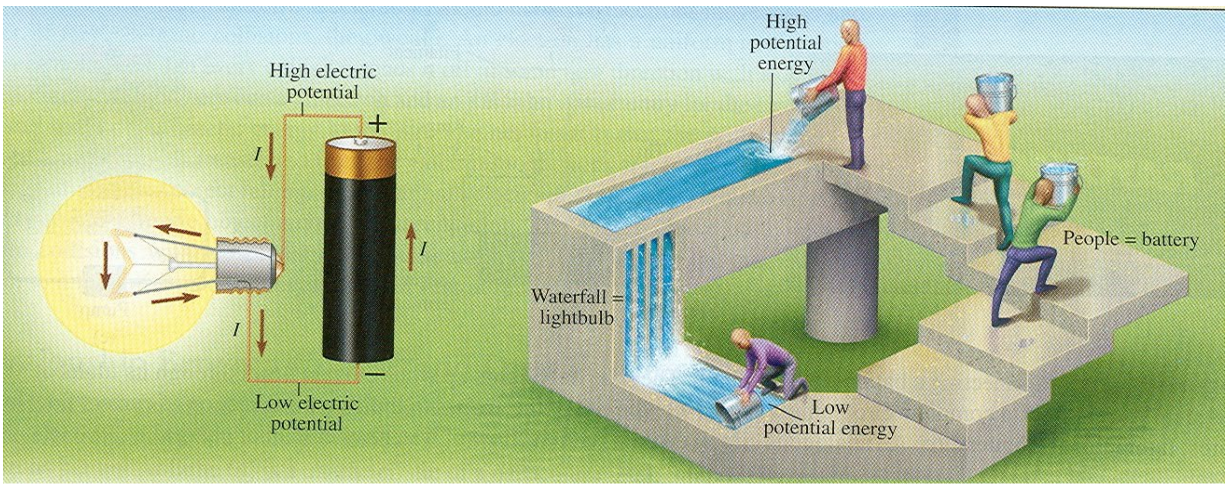
The number of free electrons per cubic metre in a copper wire is approximately 8.0×10^{28}, that is, about 1 or 2 free electron per atom. A typical diameter of wire is 1.0 mm. If the current is 1.0 A, what is the average speed of the electrons along the wire?

Example 3 shows how slowly electrons drift (often in the order of 10^{-4} m s^{-1}) along a wire, but there is no time delay between turning on a light switch and the light coming on. This is because the electric field is set up in the wire with a speed approaching the speed of light, and all the electrons start to move all along the wire at very nearly the same time. The time that it takes any individual electrons to get from the switch to the light bulb is not relevant.

A common misconception is that when a lamp, for example, is switched on, electrons somehow rush round to the lamp at a very high speed, hence it illuminates instantaneously. The magnitude of the drift velocity shows that this is quite clearly not the case. We should regard the connecting wires as being already 'full' of electrons all the way round the circuit and switching on merely starts the slow flow for all, rather like turning on a tap to start water flowing in 'full' water pipes.

Analogy between waterfall and lighting circuit

Consider the analogy of the human powered waterfall to a simple lighting circuit.



The people act as a pump, taking water from the place where its potential energy is lowest and doing the necessary work to carry it uphill to the place where its potential energy is highest. The water then runs downhill, encountering resistance to its flow along the way before returning to the point with the lowest potential energy.

With the flow of water representing the flow of <u>positive</u> charge in an electric circuit, a battery plays a role analogous to the people who carry buckets of water. A battery takes positive charges from the place where the electric potential is lowest (negative terminal of the battery) and does the necessary work to move it to the place where the electric potential is the highest (positive terminal). Then the charge flows through an electrical device (i.e. light bulb) which offers resistance to the flow of current before returning to the negative terminal of the battery.

Just as water would flow naturally from a place with higher potential to a lower potential, electric current flows from a *point of higher potential* in an electric circuit to a *point of lower potential*.

(j) distinguish between electromotive force (e.m.f.) and potential difference (p.d.) using energy considerations

When a current passes through an electrical device, electrical energy is converted into other forms of energy (i.e. heat in a resistance wire, light emitted by a lamp or mechanical energy in a motor). The amount of electrical energy converted per unit charge is called the *electricl potential difference*.

Mathematically, the electric potential difference V between two points in a circuit is given by

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

where W is the energy transformed from electrical to non-electrical energy when a charge of Q flows in that part of the circuit.

The <u>potential difference between two points</u> in a circuit may be defined as

<u>*work done per unit charge when electrical energy is transferred to non-electrical energy when the charge passes from one point to the other.*</u>

In order to maintain an electric current in an electrical circuit, a potential difference across the ends of the entire circuit is required. To achieve this, the ends of the electrical circuit may be connected to the opposite terminals of a battery.

This potential difference which is maintained by the battery is known the *electromotive force or the e.m.f. of the battery*. The e.m.f. is a measure of the work done per unit charge by the battery.

The <u>e.m.f. of a source</u> can be defined as *the*

<u>*work done per unit charge when non-electrical energy is transferred into electrical energy when the charge is moved round a complete circuit.*</u>

Electromotive Force	Potential Difference
Refers only to source.	Refers to any two points in an electrical circuit.
Considers the amount of non-electrical energy converted into electrical energy per unit charge passing through the terminals of the cell (source).	Considers the amount of electrical energy converted to non-electrical energy per unit charge passing from one point to the other.
It is a source of energy and it will exist whether or not a current is flowing in the circuit.	It can only exist if current is flowing in the electrical circuit.

(d) *recall and solve problems using the equation $V = W / Q$*

Example 4

The potential difference across a resistor is 12 V. The current in the resistor is 2.0 A. A charge of 4.0 C passes through the resistor.

What is the energy transferred in the resistor and the time taken for the charge to pass through the resistor?

	energy / J	time / s
A	3.0	2.0
B	3.0	8.0
C	48	2.0
D	48	8.0

(f) *define the resistance of a circuit component as the ratio of the potential difference across the component to the current passing through it and solve problems using the equation $V = IR$*

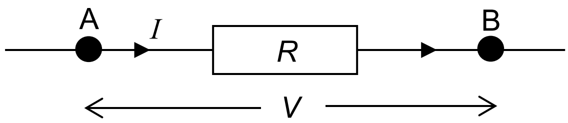
The *resistance* of a conductor is a measure of its opposition to the flow of current through itself. It is the property of a given conductor which limits the current flow.

The same analogy that compares the flow of electric charge in a wire to the flow of water in a river, or in a pipe, acted on by gravity is helpful to understand how the current through the conductor depends on the potential difference across the conductor.

If the water is nearly level, the flow rate is small. However, if one end is higher than the other, the flow rate is greater. In fact, the greater the height difference, the larger the swifter the water flow. The gravitational potential or height of the cliff is analogous to electric potential. Just as an increase in height can cause a greater flow of water, the *greater the electric potential difference*, the *larger the electric current.*

Exactly how large the current in the wire depends not only on the potential difference but also on the resistance the wire offers to the flow of electrons (current). The banks of the river or the rocks in the middle offer resistance to the flow of water. Similarly, electron flow in the conductor is impeded because of interactions with the atoms of the wire. The higher the resistance, the lesser the current for a given potential difference. So electrical resistance is such that the current is inversely proportional to the resistance.

The resistance R of a component is defined *as the ratio of the potential difference across the component to the current passing through it*.



Mathematically,

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

Ohm's Law

Georg Simon Ohm was the first to study the resistance of different materials systematically. He established experimentally that *a current (I) flowing through a conductor is directly proportional to the potential difference (V) applied across the conductor, provided that physical conditions (like temperature, stress of the material etc) remains constant*.

Mathematically:

$$I \propto V$$

Hence, an implicit characteristic of ohmic conductors is that their resistance remains a constant.

Point to Ponder

When comparing Ohm's Law ($I \propto V$) to the definition of resistance ($R = \frac{V}{I}$), it would seem that the 2 relationships are the same. Hence, is the latter just a restatement of the former?

(g) sketch and explain the I–V characteristics of various electrical components such as an ohmic resistor, a semiconductor diode, a filament lamp and a negative temperature coefficient (NTC) thermistor

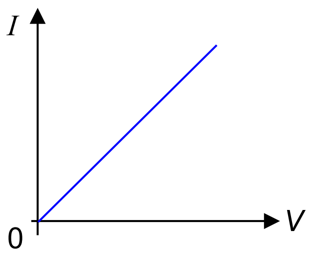
The I-V graph of a material, which is obtained experimentally, allows the resistance of the material to be determined for various values of V (or I). Why does the resistance of most materials not remain a constant?

When the current passes through a material increases, the *temperature* of the material is likely to increase. When the latter occurs, two main changes occur at the molecular level which affects the resistance of the material:

1. the number of charge carriers per unit volume, *n* (or the charge concentration) increases which reduces the resistance of the material.

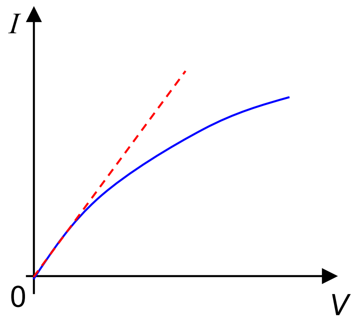
2. the thermal vibrations of the lattice atoms increases which increases the resistance of the material.

Metallic Conductor at Constant Temperature



Since the conductor is maintained at constant temperature, number of free electrons per unit volume, *n* is fixed. The amplitude of atomic vibration and the rate of collisions with the atoms remains unchanged. Thus the resistance remains a constant and the conductor is said to be ohmic.

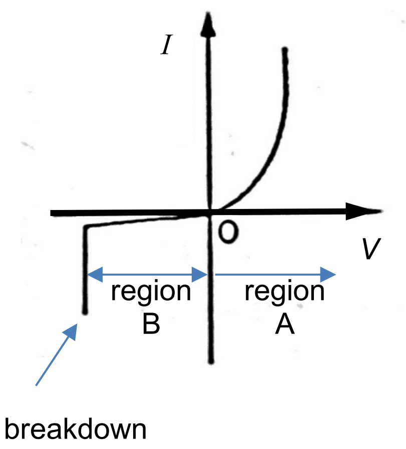
Filament Lamp



As *V* increases, *I* increases initially. Further increase of the *V* causes a less than proportionate increase in the current.

As the temperature increases, *n* will not vary significantly but the amplitude of atomic vibration increases and so does the number of collisions with the atoms per unit time. Since the increase in the rate of interaction of electrons with the lattice predominates over the increase of *n*, the overall effect is that resistance *R* increases.

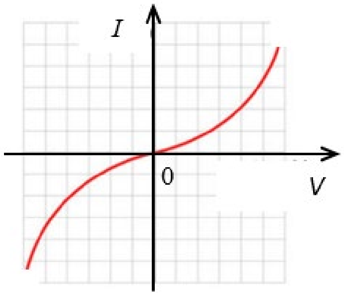
Semiconductor Diode



Considering for the *forward-biased* region (region A) of the *I*-*V* graph: As *V* increases, temperature of the semiconductor increases. Electrons in semiconductor are more likely to have sufficient energy to escape from a particular atom if the temperature is higher. This increases *n* significantly. At the same time, there is also an increase in rate of interaction of electrons with the vibrating atoms. However, as the increase in *n* predominates over the rate of interactions of electrons with the lattice, the overall effect is that resistance *R* decreases.

If the forward voltage is greater than a threshold value (0.7 V for silicon diode), then a large current will pass through the diode. Region B is known as the *reverse-biased region.* There is no current flow through the diode until the breakdown voltage (at least 50 V at room temperature).

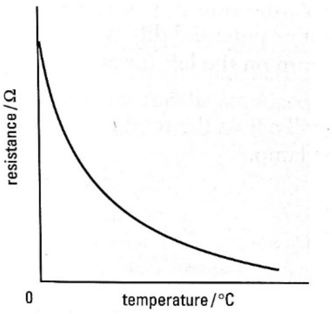
Negative Temperature Coefficient (NTC) Thermistor

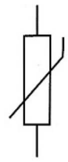


An NTC thermistor's resistance falls as the temperature rises. As the temperature increases, the number of charge carriers per unit volume in the material increases, reducing the resistance.

As such, its I-V characteristic is the same as that for a semiconductor diode for positive values of V and I.

(h) sketch the resistance-temperature characteristic of an NTC thermistor





a thermistor

Thermistors (thermal resistors) are semiconductor devices with resistances that change dramatically under different conditions.

An NTC thermistor's resistance falls as the temperature rises.

(i) recall and solve problems using the equation R= ρl / A

The resistance of a conductor depends on

- the nature of the material;
- the size of the sample (length and cross-sectional area);
- the temperature of the sample.

In many cases, the change in resistance with temperature is so small that it can be ignored except under extreme conditions.

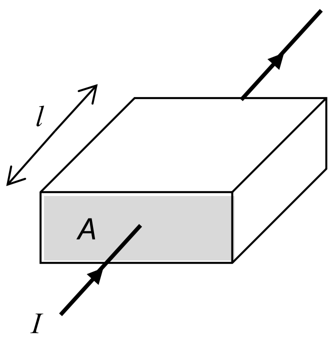
Consider the analogy of water flow through a pipe; a longer pipe offers more resistance to water flow than a short pipe while a wider pipe offers lesser resistance than a narrow pipe. Hence, one would expect electrical resistance to be greater with a longer and thinner conductor.

It is found experimentally that the resistance R of any conductor is directly proportional to its length l and inversely proportional to its cross-section area A.

Mathematically:

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

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

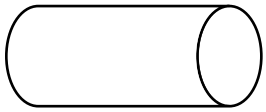


The constant of proportionality ρ, known as the *resistivity* (which depends on temperature), is the only factor in this equation governed by the nature of the material, and is independent of its length or cross-sectional area.

Metals generally have low resistivity values (of the order of 10^{-8} Ω m) whereas insulators such as rubber have high resistivity values (10^{13} ~ 10^{16} Ω m). Semiconductors have intermediate resistivity values which are highly dependent on temperature; the room-temperature resistivity of a typical semiconductor is several orders of magnitude greater than that of a typical metal.

Material	Resistivity, ρ / 10^{-8} Ω m	Temperature coefficient, α / 10^{-3} K^{-1}
copper	1.7	4.3
lead	21.0	4.3
gold	2.4	4.0
silver	1.6	4.0
nichrome	130.0	0.17
constantan	47.0	0.02

Example 5
A cylindrical wire of radius *r* and length *L* has a resistance *R*. Another wire made of a similar material has a radius *2r* and *2L*. What is the resistance of the second wire in terms of *R*?

$R = \rho \dfrac{l}{A}$		
Resistivity	ρ	
Length	L	
Cross-sectional Area	A	
Resistance	R	

(e) *recall and solve problems using the equations $P = VI$, $P = I^2R$ and $P = V^2/R$*

Potential difference *V* across two points is defined as the *work done W to transfer electrical energy to non-electrical energy* when a charge Q moves through the points, and is given by

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

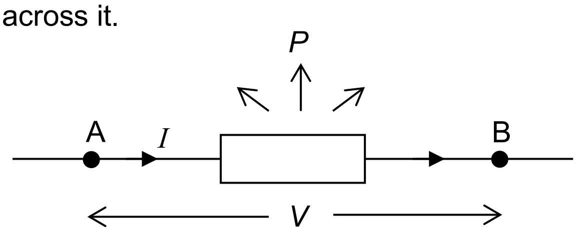
If both the numerator and denominator are divided by time *t*,

$$V = \frac{\frac{W}{t}}{\frac{Q}{t}} = \frac{P}{I}$$

The result is re-arranged to give the familiar relationship

$$\boxed{P = VI}$$

where P is the electrical power dissipated by the conductor, I is the current passing through it and V is the potential difference across it.



Using the definition of resistance, alternative expressions for power dissipated can be obtained:

$$\boxed{P = I^2R} \qquad \boxed{P = \frac{V^2}{R}}$$

Power Rating

The rated power is the rate at which energy is used (power consumption) by a device when the device is operating at the rated potential difference across it.

For an electrical device rated 100 W, 220 V, it means that when a potential difference of 220 V is applied across the terminals of the device, the device dissipates 100 W of power.

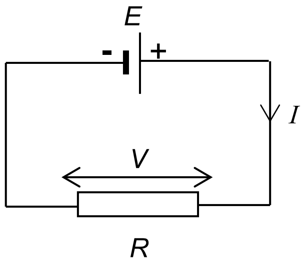
Example 6

The same potential difference is applied across a 30 W light bulb and a 60 W light bulb. These bulbs operate at their rated power only when connected to a 120 V source. Assuming the resistance of the light bulbs remain the same, which one of the following statement is true?

(a) The 30 W bulb carries a greater current and has a higher resistance.
(b) The 30 W bulb carries a greater current, but the 60 W bulb has a higher resistance.
(c) The 30 W bulb has a higher resistance, but the 60 W bulb carries a greater current.
(d) The 60 W bulb carries a greater current and has a higher resistance

(k) 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.

Consider a simple circuit consisting of a cell and a resistor.



In an *ideal* circuit,

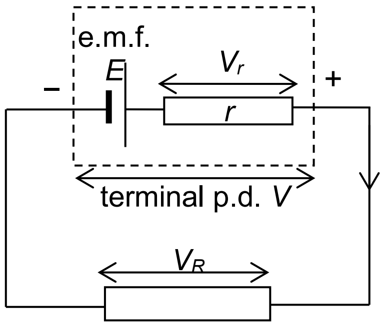
- the connecting wires would have no resistance, and
- the p.d. V across the cell terminals (terminal p.d.) = e.m.f. E of the cell.

However, **real** cells always have some internal resistance r and not all electrical energy generated is available to the external load R. Some energy is lost as heat within the source due to its internal resistance. As a result, the terminal p.d. is *not equal* to the e.m.f. of the source.

The value quoted on a cell refers to the p.d. between its terminals when no current is flowing, or when its internal resistance is zero.

Note:
The difference between 'cell' and 'battery' is that a cell is a single unit which converts chemical energy to electrical energy to deliver a voltage, while a battery can be a single cell or multiple cells connected together in series or parallel to achieve a desired voltage or / and current rating.

A **real** battery can be modelled as (a battery or a combination of cells) a resistance r, which is connected in series to an ideal e.m.f. source of e.m.f. E as shown in the dashed box below.



Within the source of e.m.f., chemical energy is converted to electrical energy,

power supplied by the source, $P_S = IE$

In the internal resistance r,

power dissipated as heat, $P_r = I^2 r = IV_r$

In the external load *R*,

power dissipated as heat, $P_R = I^2R = IV_R$

By the principle of conservation of energy,

power supplied by source = power dissipated in *r* and *R*

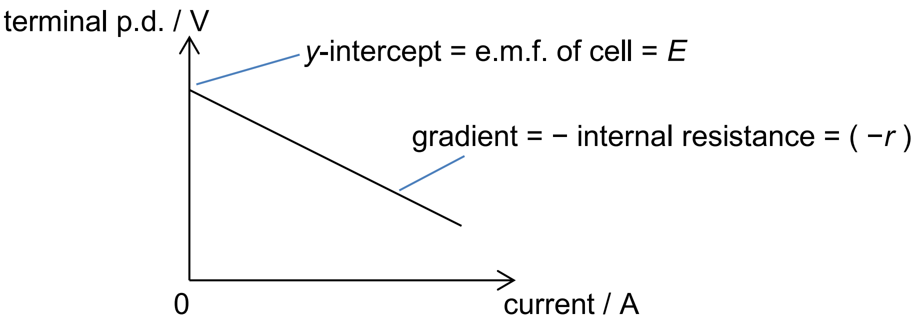
$$P_S = P_r + P_R$$
$$IE = I^2r + I^2R$$
$$\boxed{E = I(r + R)}$$

Also

$$P_S = P_r + P_R$$
$$IE = IV_r + IV_R$$
$$E = Ir + V_R$$
$$\boxed{V_R = E - Ir}$$

When a current I is flowing, the voltage drops by Ir across the internal resistance and hence the remaining voltage across the battery (terminal p.d.) will be $V = E - Ir = V_R$.

The graph of terminal p.d. against current drawn from a cell:



Example 7

(a) By considering a practical source with e.m.f. *E* and internal resistance *r* connected in series with an electrical device of resistance *R*, determine

(i) an expression for output efficiency of the source, $\eta = \dfrac{\text{useful power output}}{\text{total power generated}}$.

(ii) the value of *R* in terms of *r* such that maximum power is delivered to the device.

(b) Using your answers to part (a), discuss the effect on the output efficiency of a source when it is used to operate an electrical device at maximum power.

Definition List

Electric Charge, *Q*	A property of some elementary particles (particles of matter that cannot be subdivided into smaller matter) that causes them to exert forces on one another. Charge is given by the integral of electric current with time. Q = $\int I$ dt. If the rate is constant or if the current is steady, then amount of charge (Q) passing through a given section of a conductor is the **product** of the steady current I that flows past the section and the time interval *t* during which the current flows. Q = I t
Electric Current	A flow of charged particles, which may be positively or negatively charged.
Potential difference (p.d.)	The potential difference between two points in a circuit is the <u>work done per unit charge</u> when <u>electrical energy is transferred to non-electrical energy</u> when the charge passes from one point to the other.
Electromotive Force, e.m.f.	The electromotive motive force of a source can be defined as the <u>work done per unit charge</u> when <u>non-electrical energy is transferred into electrical energy</u> when the charge is moved round a complete circuit.
Resistance (2004, 2011)	The resistance *R* of a conductor is defined as the **ratio** of the potential difference across the conductor to the current passing through it.
Internal resistance	Resistance to movement of charge (current) within an electrical power source causing energy loss in the source.
Resistivity, ρ (2011)	Resistivity is a relationship between the dimensions of a specimen of a material and its resistance that is constant at constant temperature. Resistivity is calculated by ρ = $\frac{RA}{L}$ where *R* is resistance, *A* is cross-sectional area and *L* is length. Note: Resistance is a property of the sample whereas resistivity relates to the material itself.
Maximum Power Theorem	Maximum power is supplied to the external circuit when the resistance of the external circuit is equal to the internal resistance of the cell.

Tutorial Questions

1. The current in the electron beam of a computer monitor is 320 μA. How many electrons hit the screen per second? [2.0×10^{15}]

2. A copper wire carries current from the brake pedal switch to the brake light on a car. The wire has a cross-section of 1.0 mm^2, and is 6.0 m long. If the current in the wire is 2.0 A when the light is on, estimate how long it takes an electron in the wire to travel from one end to the other. The number of free electrons per cubic metre in a copper wire is approximately 8×10^{28}. [3.8×10^4 s]

3. A bird stands on a d.c. transmission line carrying 2800 A. The line has 2.5×10^{-5} Ω per metre and the bird's feet are 4.0 cm apart. What is the potential difference between the bird's feet? [2.8×10^{-3} V]

4. A wire of resistance *R* is stretched uniformly until it is twice its original length. Assuming the density of the wire does not change significantly, what is its new resistance in terms of *R*? [4*R*]

5. A water heater is marked 230 V, 3000 W. It is switched on for 5000 s. For this heater, calculate

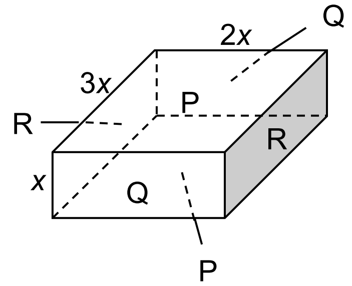
(a) the current through the heater, [13 A]

(b) the resistance of the heater, [17.6 Ω]

(c) the energy supplied by the heater during this time. [1.5×10^7 J]

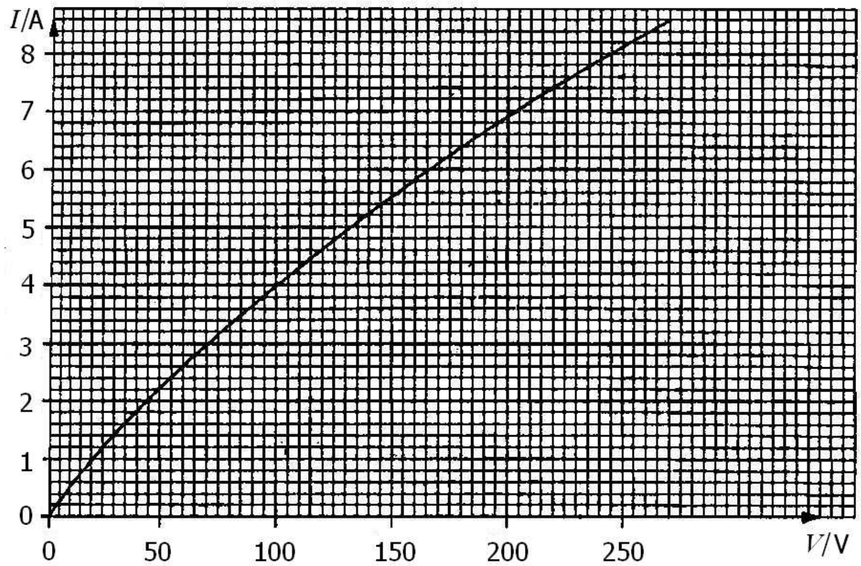
6. A generator produces 100 kW of power at a potential difference of 10 kV. The power is transmitted through a cable of total resistance 5.0 Ω. What is the power loss in the cable? [500 W]

7. The diagram shows a rectangular block with dimensions *x*, 2*x* and 3*x*.



Electrical contacts to the block can be made between opposite pairs of faces of the block (i.e. between the faces marked R). Between which two faces would maximum electrical resistance be obtained?

8. One element of an electric cooker has an I-V characteristic as shown.



(a) Explain how the characteristic shows that the resistance of the element increases with potential difference.

(b) Explain in terms of the movement of charged particles why the resistance increases with potential difference.

(c) Use the graph to estimate the potential difference which should be applied to the element if it is to have a resistance of 30 Ω. [225 V]

(d) What will be the current in the element when it has a resistance of 30 Ω? [7.5 A]

(e) What will be the power of the element when it has a resistance of 30 Ω? [1690 W]

9. A battery has an e.m.f. of 12.0 V and an internal resistance of 0.05 Ω. Its terminals are connected to a load resistance of 3.00 Ω.

(a) Find the current in the circuit and the terminal potential difference of the battery.

[3.93 A, 11.8 V]

(b) Calculate the power delivered to the load resistor, the power delivered to the internal resistance of the battery, and the power delivered by the battery.

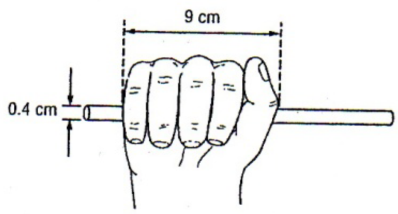
[46.3 W, 0.772 W, 47.2 W]

(c) As the battery ages, its internal resistance increases. Suppose the internal resistance rises to 2.00 Ω toward the end of its useful life. How does this affect the ability of the battery to deliver energy?

10. The resistivity of the human body is low compared with the resistivity of skin which is about 3×10^4 Ω m for dry skin.

(a) For a layer of dry skin 1 mm thick, determine the resistance of a 1 cm^2 area of skin. [3.0×10^5 Ω]

(b) A person, who is well earthed, accidentally grabs an uninsulated wire of diameter 0.4 cm at a potential of 50 V. His hand makes contact with the whole circumference of the wire over a distance of 9 cm as shown.



The average thickness of skin of his hand is 1 mm. Estimate the current through the person. [1.88 mA]

(c) Discuss two factors, referred to above, which affects the magnitude of the current and hence the possible danger from electric shock. One obvious safety precaution is to keep live wires well insulated. What other safety precautions do you suggest?

11. You are provided with two identical resistors and a d.c. power supply. What arrangement of resistors would give greatest power dissipated in the resistors when connected to the power supply?

12. When a battery of e.m.f. of 6.0 V is connected to a load of resistance *R*, the power dissipated in this load is 8.2 W. If the terminal potential difference of the battery is 5.7 V, determine

(a) the load resistance *R*, and [3.96 Ω]

(b) the internal resistance *r* of the battery. [0.21 Ω]

13. **(a)** The *I*-*V* characteristic graph for a thermistor is shown in Fig. 13.1

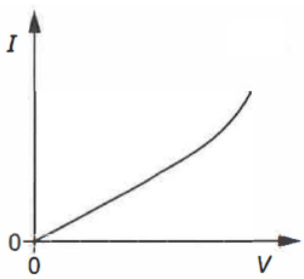


Fig. 13.1

Describe and explain what this graph shows about the resistance of the thermistor as the potential difference (p.d.) across it is increased from zero . [2]

(b) Two resistors are connected to a d.c. power supply with negligible internal resistance. One resistor has a resistance of 220 Ω and the other has a resistance of 640 Ω. They can be connected in series, as shown in Fig. 13.2, or in parallel, as shown in Fig. 13.3.

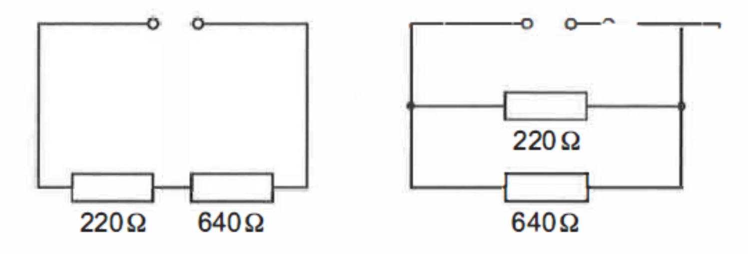


Fig. 13.2 **Fig. 13.3**

(i) For the two resistors connected in series, show that the ratio:

$$\frac{\text{power dissipated in 220 }\Omega\text{ resistor}}{\text{power dissipated in 640 }\Omega\text{ resistor}} = 0.34$$

Explain your working. [2]

(ii) The power supply is replaced with another supply that has an internal resistance.

State and explain the effect on the ratio of the powers in **(b)(i)**. [1]

(iii) For the original power supply with negligible internal resistance, calculate the ratio:

$$\frac{\text{current from supply in series circuit}}{\text{current from supply in parallel circuit}}$$

Show your working. [3]

(iv) The power supply is now replaced with an a.c. power supply that has negligible internal resistance. Its peak voltage is equal to the value of the output voltage from the d.c. power supply.

State and explain the effect on the ratio of the currents in **(b)(iii)**. [1]

14. Data based Question

The variation with temperature of the resistance of a thermistor is shown in Fig. 14.1.

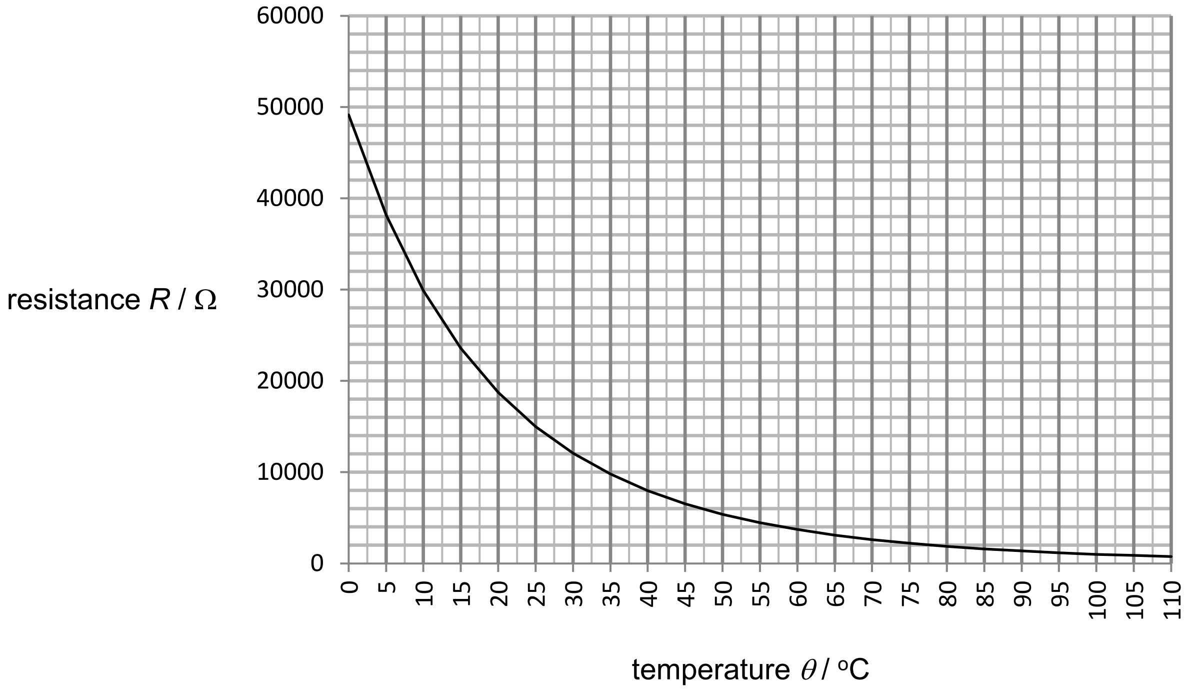


Fig. 14.1

(a) Some data from Fig. 14.1 are used to plot the graph of Fig. 14.2. [Take $T = 273 + \theta$]

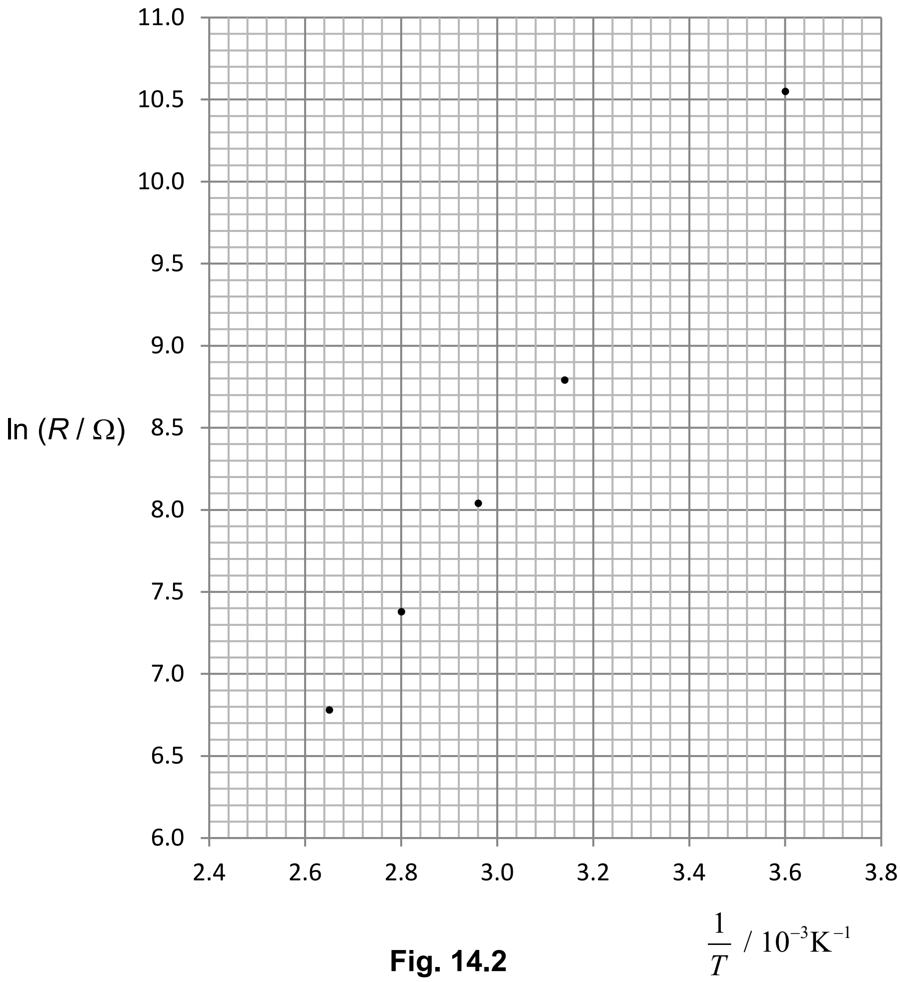


Fig. 14.2

The relation between resistance R and T is thought to follow the expression

$$R = Ae^{\frac{B}{T}} \text{ where } T \text{ is in kelvin.}$$

(i) Use Fig. 14.1 to determine ln (R/Ω) for a temperature θ of 25 °C. [9.62]

(ii) On Fig. 14.2,

1. plot the point corresponding to temperature θ of 25 °C,

2. draw the line of best fit for the points.

(iii) Use the line drawn in **(ii)** to determine the constants A and B in the expression in **(a)**. [A = 0.0238 Ω, B = 3976 K]

(b) **(i)** This thermistor is more sensitive when used as a thermometer in low temperature measurements. Suggest a reason for this based on Fig. 14.1.

(ii) A thermistor is made up of semiconductor material. Suggest a reason why the resistance decreases as temperature increases.

(iii) Fig. 14.3 shows the variation with temperature of the resistance of some common materials in comparison with a thermistor.

	at 20 °C	at 100 °C
A copper wire	1.0 Ω	1.3 Ω
A wire of constantan	31.0 Ω	31.1 Ω
Bead thermistor	5000.0 Ω	80.0 Ω

Fig. 14.3

1. Describe the main difference in the variation with temperature of the resistance between the bead thermistor and the two other metals.

2. A device is used in motors to limit a possible surge of current when the motor is switched on at a temperature of 20 °C. Suggest why it is preferable for the device to be a bead thermistor rather than a constantan wire.

(c) A circuit suitable for temperature measurement is a Wheatstone bridge with a thermistor used as one bridge leg as shown in Fig. 14.4. Any change in temperature will cause a change in the value of the thermistor R_T so that there is a significant potential difference between X and Y which is connected to a data logger.

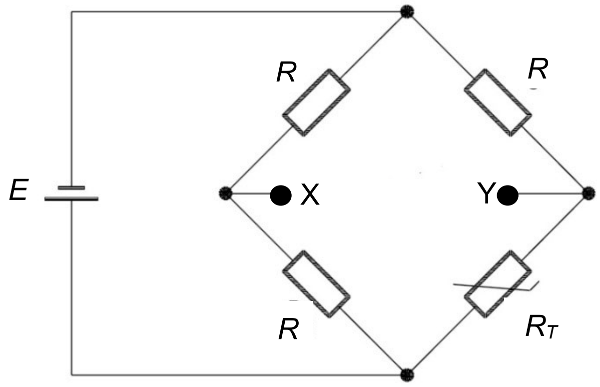


Fig. 14.4

The potential difference between Y and X is given as $V_{YX} = \dfrac{R - R_T}{2(R+R_T)}E$. A thermistor with the characteristics shown in Fig. 14.1 is used. The temperature of the system to be measured has a range from 5 °C to 40 °C.

If the value of *R* used is 40 kΩ and *E* is 10 V, determine the minimum and maximum value of V_{YX}. [0.128 V, 3.33 V]