Chapter 14 CURRENT OF ELECTRICITY

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 for a current-carrying conductor $I = nAv_Dq$, where n is the number density of charge carriers, q is the charge and v_D 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 equation $P = IV$, $P = I^2R$ 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 $R = \rho l / A$

(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.

14.1 Electricity

Introduction

In the year 1800, the concept of electric current was not yet known. Alessandro Volta had invented the first battery, then known as the voltaic pile. 20 years later, Hans Christian Øersted demonstrated 'electrical conflict' during a lecture: by the heating of a wire which was attached to the poles on a voltaic pile. A compass needle which had, *by chance*, been placed on the table showed a slight rotation.

Also in 1820, André Marie Ampère discovered that the essence of electric current is *charge transport*. He traced the current to current interaction and postulated that the current is always the cause of the magnetism, and that permanent mysterious circulating currents always flow in a permanent magnet, which was proved by experiment nearly 100 years later by Einstein and Johannes Wander de Haas.

Another of Ampère's discoveries was an experimental trick which appears so trivial today that its ingenuity is hardly ever acknowledged: Ampère invented the coil. Ever since then, it has been possible for science and technology to produce strong magnetic fields.

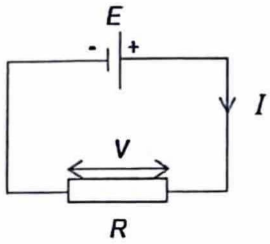
A year later in 1821, Michael Faraday postulated that if current generates magnetism, it should also work the other way around. He then spent 11 years looking for such a device and finally in 1831, discovered the *electromagnetic induction*: when a primary current in a ring-shaped transformer set-up was switched on and off, this induced a current surge in a secondary coil, which could be traced by a compass needle. What, for Faraday, was a barely traceable, weak effect, is today an indispensable instrument in technology. From bicycle dynamos to nuclear power stations, the aim is always to get a coil to move in a magnetic field.

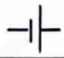
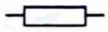
In *Current of Electricity*, situations involving charges moving continuously in a closed electrical circuit is discussed. The term *electric current*, or simply *current*, is defined as the rate of flow of charge through some region of space.

Electric current is essential for many machines and appliances which run on electricity to function. Our mobile devices such as handphones and laptops as well as larger appliances such as a mainframe computer and the air conditioner will be rendered useless without electric current. In such instances, a current exists in a conductor such as a copper wire, which is part of a larger closed electrical circuit.

14.2 Current of Electricity

Electrical Circuit



Circuit Element	Symbol	Units
A cell or battery of electromotive force (e.m.f.), E		Volt V
Resistor of resistance R		Ohm Ω
Direction of conventional current, I		Ampere A

The figure above shows a simple, closed electrical circuit constituting a source of electromotive force (e.m.f.) E, e.g. a cell or a battery which is connected in series with a resistor of resistance R by means of connecting wires which are assumed to have zero resistance.

The connecting wires provide a continuous conducting path for electrical charges to flow from the positive terminal of the source of e.m.f. through one or more devices such as the resistor, and then back to the negative terminal of the source. To analyse such a closed circuit, we shall now look at the different components of the electrical circuit and discuss some important terms.

14.3 Electric Current I & Charge Q

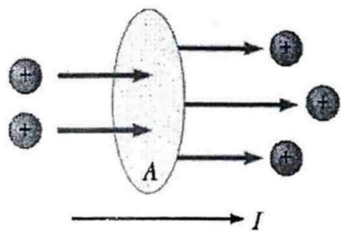
Electric Current I and Its Unit

Definition

Whenever charged particles move, an electric current is said to exist.

Electric current is defined as the rate of flow of charge.

Suppose charge is moving perpendicular to a surface of area A as shown in the figure below. The area A could be the cross-sectional area of a conducting wire.



If ΔQ is the amount of charge passing through this surface in a time interval Δt, the **average electric current** I_{ave} is equal to the net charge that passes through the area per unit time i.e.

$$I_{ave} = \frac{\Delta Q}{\Delta t}$$

The S.I. unit for current is the **ampere**, A, and it is one of the seven base units of physical quantities.

If the rate at which charge flows varies with time, the **instantaneous current I** is defined as the differential limit of the average current i.e.

$$I = \lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t} = \frac{dQ}{dt}$$

Charge Q and Its Unit

Electrical charge is a fundamental property of matter which causes a charged object to experience a force when placed in an electric field. When a constant current I flows through a cross-section of a conductor for a duration t, the amount of **electrical charge** Q passing through it is given by

$$Q = It$$

The S.I. unit for electric charge is the **coulomb,** C.

One **coulomb** is defined as the amount of electrical charge that passes through a point in one second when there is a constant current of one ampere ($1\,\text{C} = 1\,\text{A s}$).

Another unit of charge is milliampere hour, mAh (1 mAh = 3.6 C).

If the current flow is not constant, from equation (2),

$$Q = \int I\,dt$$

Types of Charge Carriers

By convention, the direction of current is defined as the direction of flow of positive charge, regardless of the actual sign of the charged particles in motion. The types of charged particles may vary for different types of conductors.

In metals, electric current is the result of motion of free electrons. Therefore, the direction of the current is opposite to the direction of flow of electrons.

In some cases such as in charged gases and electrolytes, electric current is the result of the motion of both the positively and negatively-charged particles. It is common to refer to a moving charged particle, regardless of its sign, as a mobile or free charge carrier.

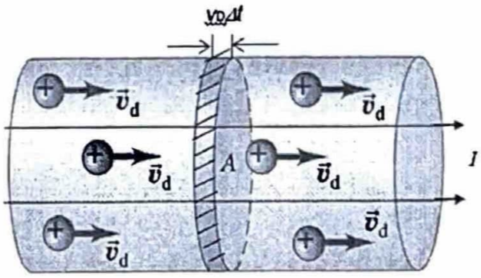
The table below shows examples of charge carriers in different materials.

Material	Charge Carriers	Examples	Remarks
Metals	electrons	copper, silver, aluminium	Each atom of the metal supplies one or more free electrons from its outer shell to form the bond necessary to hold the positive ions together. These electrons are highly mobile and contribute to electrical current.
Semi-conductors	electrons and (positive) holes	germanium, silicon (group 4 metals)	All four electrons in the outer shell are shared among neighbouring atoms to form covalent bonds. At room temperature, these electrons may have sufficient energy to leave the atoms to become "free" electrons. They leave behind "holes" where neighbouring electrons can move to fill them, leaving holes from where they came from. In this way, the holes seem to behave like positively charged particles moving in the opposite direction to the flow of elections.
Electrolytes	ions	sodium chloride solution	Some salts dissociate into ions when dissolved in water. These ions are either positively or negatively charged, and they are mobile. Hence, they contribute to electrical current.
Insulators	none	rubber, porcelain, glass	All electrons in the outer shell of the atoms of an insulator are involved in forming covalent bonds. Unlike semi-conductors, these electrons cannot acquire sufficient energy to be "freed", and they are not available for electrical conduction.

Drift Velocity v_D and Electric Current I

When there is an electric current in a conductor, the free charge carriers in the conductor move with an average velocity in the order of 10^{-4} m s^{-1}. This is called the **drift** velocity, v_D.

Consider a conductor with cross-sectional area A (perpendicular to the direction of current flow) and n charge carriers per unit volume (or the number density). A current I flows to the right as shown in the following figure.



In a time interval Δt, each charge carrier, assumed to be positive, moves a distance $v_D(\Delta t)$ to the right. Thus, in Δt, charges within a distance of $v_D\Delta t$ to the left of the cross-section A (the shaded cylinder) will pass through A. The volume of the shaded cylinder is $Av_D(\Delta t)$. The number of charge carriers passing through A in Δt is thus $nAv_D(\Delta t)$. Given that the charge carried by each charge carrier is q, the total charge passing through A in Δt is $nAv_D q(\Delta t)$. The current is then given by

Formula

$$I = \frac{\text{Total charge through } A \text{ in } \Delta t}{\text{Time interval } \Delta t} = \frac{nAv_D q(\Delta t)}{\Delta t}$$

$$\Rightarrow I = nAv_D q$$

14.4 Potential Difference V

Potential Difference V and Its Unit

If a conductor is connected to a battery, the points in the conductor are **not** at the same electric potential. The battery sets up a ***potential difference***, and hence an electric field exists across the conductor. The electric field exerts a force on the free charge-carriers in the conductor, causing them to move, resulting in a flow of electrical current.

In any system, the direction of the current is that of the motion of positive charge carriers, which move from a higher potential to a lower potential since the electric field is directed towards the lower potential.

In the case of a battery, the charge carriers are electons. Since they are negatively charged, they move from the lower potential to the higher potential, in the opposite direction to that of the electrical current.

Definition

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

Hence, the potential difference V between two points **in a circuit** is given by

Formula

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

where W is the electrical energy converted to other forms of energy in J and
Q is the net amount of charge that passes from one point to the other in C.

The S.I. unit for potential difference is the **volt,** V.

One **volt** is the potential difference between two points in a circuit when one joule of electrical energy is converted to other forms of energy as one coulomb of charge passes from one point to another ($1\text{ V} = 1\text{ J C}^{-1}$).

If a charge Q flows in a part of a circuit across which there is a potential difference V, the electrical energy converted to other forms in that part of the circuit is given by

Formula

$$W = QV$$

Example 1

A lamp has a potential difference of 10 V across it. Calculate how much electrical energy is converted to light and thermal energy when
(a) a charge of 350 C passes through it,
(b) a current of 3.0 A passes through it for 30 s.

a)
$$\begin{aligned} W &= QV \\ &= (350)(10) \\ &= 3500\text{ J} \end{aligned}$$

b)
$$\begin{aligned} W &= QV \\ &= (It)V \\ &= (3.0 \times 30)(10) = 900\text{ J} \end{aligned}$$

Example 2

An immersion heater, rated at 1000 W, is switched on for 900 s. During this time, a charge of 3700 C is supplied to the heater. Determine the potential difference across the heater.

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

$$\therefore V = \frac{Pt}{Q} = \frac{(1000)(900)}{3700} = 243\text{ V}$$

14.5 Electromotive Force (e.m.f.) *E*

E.m.f. *E* and Its Unit

When electric current flows through conductors in a closed circuit, electrical energy is continuously dissipated as heat or other forms of energy. In order to sustain this constant flow of electric current, a source of electromotive force (e.m.f.) is needed.

Sources of e.m.f. are devices which can be likened to a "charge pump" in which electrical energy is converted from chemical, mechanical or other forms of energy e.g. batteries, generators, solar cells and fuel cells etc.

Definition

The **electromotive force (e.m.f.) of a source** is defined as the amount of electrical energy per unit charge that is converted *from* other forms of energy when charge passes through the source.

Formula

In equation form,

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

The S.I. unit for e.m.f. is also the **volt, V**.

It is important to note that e.m.f. is **not** a force as the name may suggest.

As an example, for a battery with an e.m.f. of 1.5 V, 1.5 J of chemical energy is converted into electrical energy with every coulomb of charge the battery drives through the circuit.

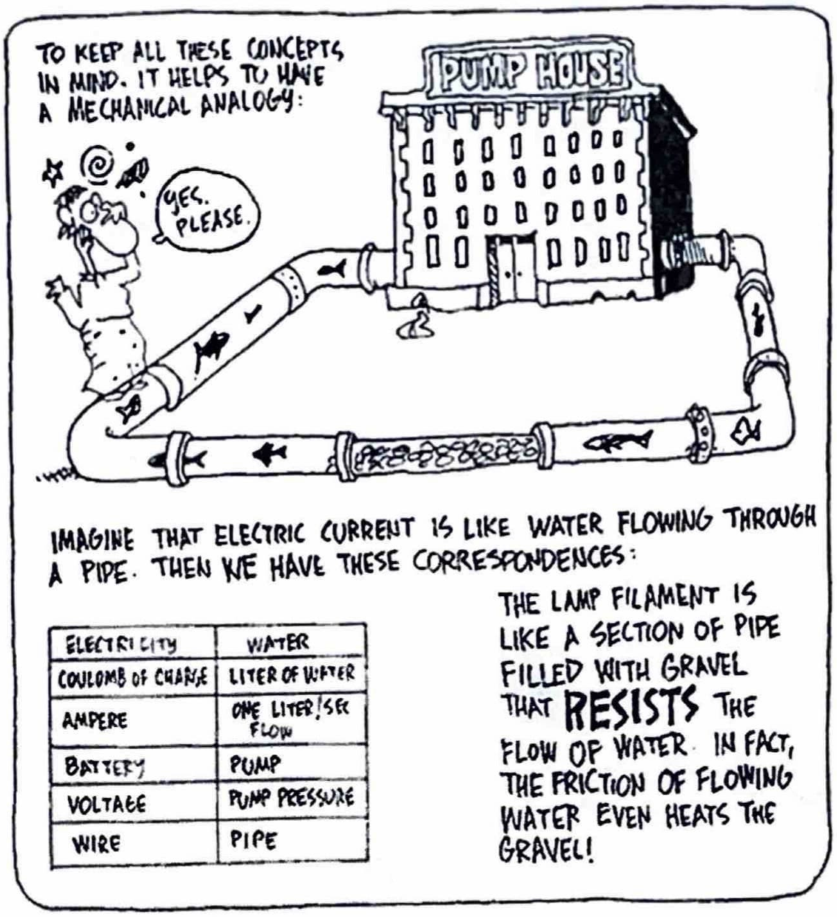
Comparing p.d. & e.m.f.

p.d. *V* across an external load	**e.m.f. *E* of a source**
$V = \frac{W}{Q}$	$E = \frac{W}{Q}$
W is the energy converted **from electrical energy** to other forms	*W* is the energy converted **from other forms** to electrical energy

14.6 Resistance R & Resistivity ρ

Resistance R and Its Unit

The electric current in a conductor depends on the potential difference applied across the conductor and its resistance.



Definition

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

In equation form, electrical resistance is given by

Formula

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

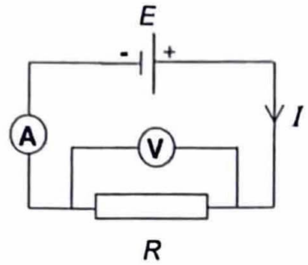
The S.I. unit for resistance is the **ohm, Ω**.

One **ohm** is the resistance of a circuit component when a potential difference of one volt across it causes a current of one ampere to flow through it ($1\ \Omega = 1\ \mathrm{V\ A^{-1}}$).

Determining R

A simple way to determine the resistance of a circuit component is to connect

1. an **ideal ammeter,** assumed to have no resistance **in series** with the component and
2. an **ideal voltmeter** which is assumed to have infinite resistance **in parallel** with the component as shown.



The ammeter measures the current flowing through the component and the voltmeter measures the p.d. across it. The resistance can thus be determined using $R = \frac{V}{I}$

Example 3

A car stereo system draws a current of 400 mA when connected to a 12.0 V battery.

(a) Calculate the resistance of the stereo system.

(b) The stereo is left playing from the battery for several hours while the engine is turned off. The radio can continue to operate until the current drops to 320 mA. Calculate the p.d. across the stereo when it stops playing.

a) $R = \frac{V}{I}$

$= \frac{12.0}{400 \times 10^{-3}} = 30.0\ \Omega$

b) Assume R to be constant

$V_{min} = I_{min} R = I' R$

$= (320 \times 10^{-3})(30.0)$

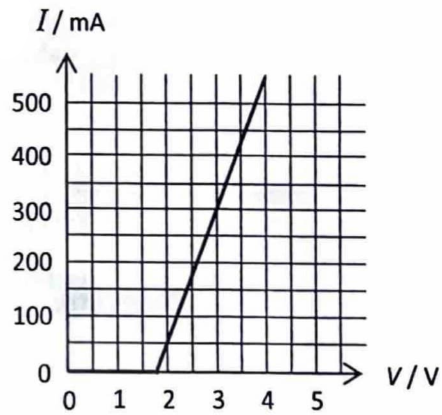
$= 9.60$ V

Example 4

The graph below shows the relationship between the direct current I in a certain conductor and the potential difference V across it. When $V < 1.8$ V, the current is negligible. Determine the resistance of the conductor when the p.d. is 3.0 V.

From Graph, when $V = 3$ V, $I = 300$ mA

$R = \frac{V}{I} = \frac{3}{300 \times 10^{-3}} = 10\Omega$



Note:
Realise that R is the ratio of V to I, and not the reciprocal of the gradient of the graph!

Ohm's Law

Definition

Ohm's law states that the potential difference across a conductor is proportional to the electric current passing through it, provided that its temperature remains constant.

The constant of proportionality is the resistance of the conductor.

Materials which obey this relationship are said to obey Ohm's law and they are said to be *ohmic*. Materials and devices that do not obey Ohm's law are *non-ohmic*.

Ohm's law is not a fundamental law of nature; rather it is an empirical relationship valid only for certain materials and devices, and only over a limited range of conditions.

Resistivity of Conductors

Resistance of a uniform[1] conductor (at a given temperature) is

(i) directionally proportional to its length l, and
(ii) inversely proportional to its cross-sectional area A,

Formula

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

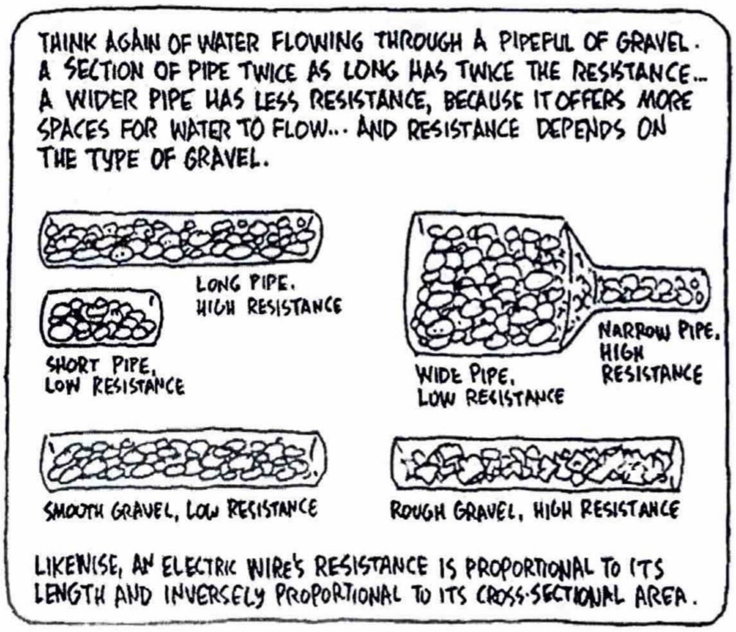
$$\text{or} \quad R = \rho\frac{l}{A}$$

Resistivity ρ and Its Unit

where the constant of proportionality ρ is called the resistivity of the material.

The S.I. unit for resistivity is the **ohm metre,** Ω m.

A useful analogy:



Every material has a characteristic resistivity. Good electrical conductors have low resistivities and insulators have high resistivities.

[1] 'Uniform conductor' here refers to a conductor that is made of a single type of material.

Semi-conductors

The resistance of pure semiconductors is between that of a conductor and that of an insulator. By introducing controlled amounts of impurities, their resistivities can be significantly reduced. This property makes them an ideal material for fabrication of computer chips and other electronic devices.

Resistivities of common materials

The following table shows a list of resistivities of some common materials at 20°C.

Type	Material	Resistivity, ρ / Ω m
Conductors	Aluminium	2.8×10^{-8}
	Copper	1.7×10^{-8}
	Gold	2.4×10^{-8}
	Iron	10×10^{-8}
	Silver	1.6×10^{-8}
	Tungsten	5.6×10^{-8}
Pure Semiconductors	Germanium	0.60
	Silicon	2300
Insulators	Glass	10^{7} to 10^{10}
	Rubber	10^{13} to 10^{16}
	Sulphur	10^{15}

* Note: The resistivity of semiconductors greatly depends on the amount and type of impurities added.

Example 5

Calculate the resistance of a tungsten filament of length 4.0 cm and diameter 0.020 mm at 20°C.

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

$$= \left(5.6\times10^{-8}\right)\frac{4.0\times10^{-2}}{\pi\left(\frac{0.020\times10^{-3}}{2}\right)^{2}} = 7.13\ \Omega$$

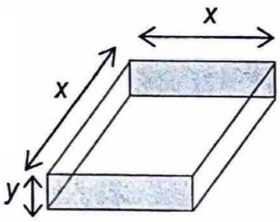
Example 6

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

$$R = \rho\frac{l}{A} = \rho\frac{x}{xy} = \frac{\rho}{y}$$

Hence, *R* is independent of *x*

A proportional to x^2
B proportional to x
C independent of x
D inversely proportional to x
E inversely proportional to x^2



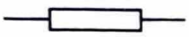
I-V Characteristics of Circuit Components

By looking at how the current I through a material varies with the potential difference V (p.d.) across it, it is possible to differentiate between ohmic and non-ohmic materials/devices.

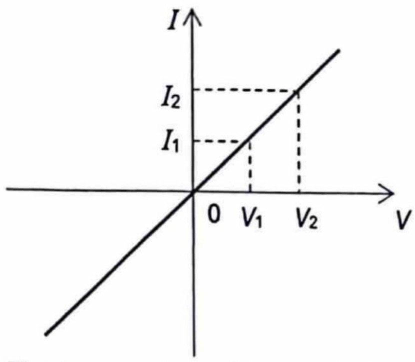
1. Ohmic Conductors (*Metallic Conductor at Constant Temperature*)

Experimentally, it has been found that if the **temperature** of a metallic conductor is **kept constant, its resistance remains constant**. The metallic conductor is of an **ohmic** material.

The I-V characteristic for an ohmic conductor e.g. a resistor at constant temperature is a **straight-line graph through the origin** as shown in the figure below.



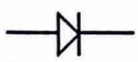
Circuit symbol for an ohmic resistor



- any increase in p.d. produces a proportionate increase in current (i.e. $I \propto V$)
- ratio $\frac{V}{I}$ is constant
- resistance, $R = \frac{V_1}{I_1} = \frac{V_2}{I_2} =$ constant

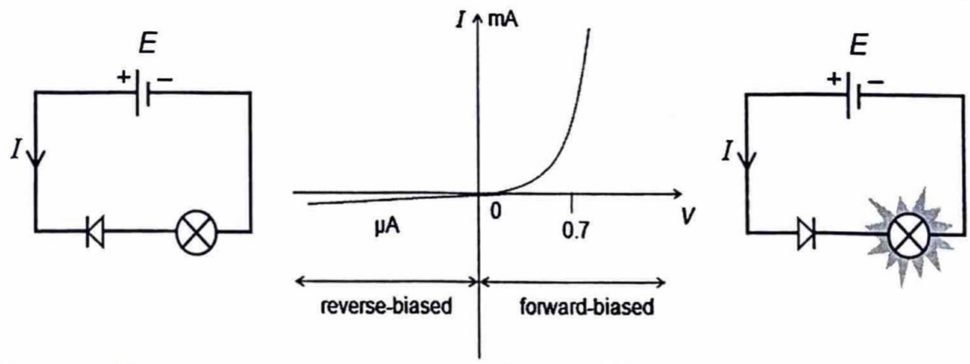
The temperature of the conductor can be kept constant by immersing the conductor in a constant temperature bath.

2. Diodes



Circuit symbol for a diode

A diode is a semiconductor device which allows current to flow in one direction only.



Reverse-bias
- Current through a diode is very small. (a few μA and appears to be zero on the graph.)
- Resistance is very high.

Forward-bias
- Current through a diode increases very rapidly when the $V > 0.7$ V (turn-on voltage),
- Resistance is very low.

Effect of Temperature (non-ohmic behaviour)

As current increases, more charge carriers move through the conductor per unit time which results in more collisions with the lattice ions. This **increases the temperature** of the conductor, which affects its resistivity in two ways:

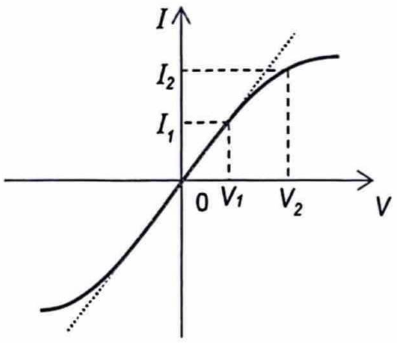
1. Electrons gain enough energy to break free, which results in an **increase in the number density of charge carriers**. ➡ **conductivity** increases!
2. Lattice ions gain thermal energy and start to vibrate faster with greater amplitude. This causes **more collisions** between the charge carriers and the lattice ions which in turn **slows down the movement of charge carriers**. ➡ **resistivity** increases!

3. Non-Ohmic conductors

How the resistivities of the various conductors change due to an increase in their temperatures depend on which of the two effects is the dominant one.

(a) Filament lamp

Effect 1 (conductivity)	**Effect 2** (resistivity)	**Result**
▪ electrons are already free and mobile at room temperature ▪ as temperature increases, there is <u>no appreciable increase in number of conducting free electrons</u>	▪ frequency of collision between lattice ions and electrons increases ▪ movement of charge carriers slow down	resistivity increases more than conductivity

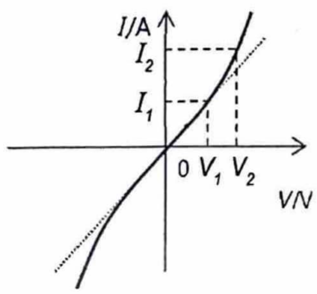


- as current increases, temperature increases
- resistivity and hence resistance increases i.e. $R = \frac{V_1}{I_1} < \frac{V_2}{I_2}$
- ratio $\frac{V}{I}$ increases
- curve gets more gentle

(b) Thermistor (NTC)

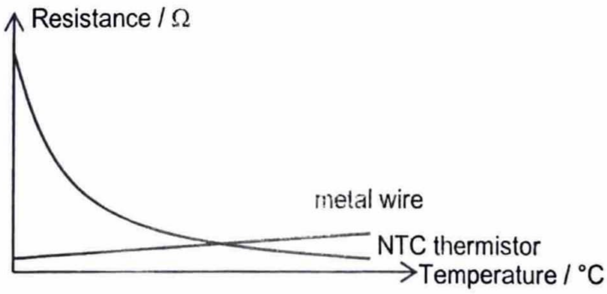
Semiconductors are in general poor conductors at relatively low temperatures due to the small number of free electrons compared to that in metals

Effect 1 (conductivity)	**Effect 2** (resistivity)	**Result**
▪ as temperature increases, more electrons acquire energy to break free from their atoms ▪ <u>number of charge carriers increases significantly</u>	▪ frequency of collision between lattice ions and electrons increases ▪ movement of charge carriers slow down	conductivity increases more than resistivity



- as current increases, temperature increases
- resistivity and hence resistance decreases i.e. $R = \frac{V_1}{I_1} > \frac{V_2}{I_2}$
- ratio $\frac{V}{I}$ decreases
- curve gets more steep

Resistance vs Temperature



14.7 Electrical Power P

Electrical Power P and Its Unit

As shown earlier, if a charge Q moves through a p.d. V, the amount of electrical energy converted to other forms is $W = QV$

The rate at which **energy conversion** takes place is

$$P = \frac{dW}{dt} = \frac{d(QV)}{dt} = \frac{dQ}{dt}V = IV$$

$$\Rightarrow P = IV$$

Formula

This equation applies for any electrical device.

The S.I. unit for power is the **watt,** W. (1 W = 1 J s^{-1})

Power Supplied by an Ideal Source

For an ideal source of e.m.f. E, work done by the source is

$$W = QE$$

The power P supplied by the source

$$P = \frac{dW}{dt} = \frac{dQ}{dt}E$$

Formula

$$\therefore \quad P = IE$$

Power Dissipated by a Resistor

The p.d. across a resistor is $V = IR$

The rate at which energy is dissipated across a resistor is

$$P = IV$$

$$\text{or} \quad P = I \times (IR) = I^2R$$

Formula

$$\text{or} \quad P = \left(\frac{V}{R}\right) \times V = \frac{V^2}{R}$$

Alternative unit of energy - the kilowatt-hour (kWh)

To measure the consumption of electrical energy, the unit **kilowatt-hour (kWh)** is sometimes used instead of the joule (J).

One kilowatt-hour is the electrical energy consumed in one hour by a device with a power rating of one kW.

(Note: $1\ \text{kWh} = 1000\ \text{W} \times 3600\ \text{s} = 3.6 \times 10^6\ \text{J}$)

Example 7

A 12 V home-made electric heating element has a power of 20 W. The heating element is to be made from nichrome ribbon of width 1.0 mm and thickness 0.050 mm. Calculate

(a) the length of ribbon required, and

(b) the cost of running the heating element for 5 hours, if electricity costs \$0.17 per kWh.

[Resistivity of nichrome is 1.10×10^{-6} Ω m]

a)

current through resistor, $I = \dfrac{P}{V} = \dfrac{20}{12}$

resistance $R = \dfrac{V}{I} = \dfrac{12}{20/12} = 7.2\ \Omega$

Sub into $R = \rho \dfrac{l}{A}$

$$l = \frac{AR}{\rho} = \frac{\left[\left(1.0 \times 10^{-3}\right)\left(0.050 \times 10^{-3}\right)\right] \times 7.2}{1.10 \times 10^{-6}} = 0.327\ \text{m}$$

b)

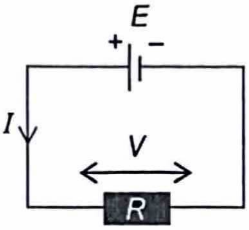
$E = Pt = 0.020 \times 5 = 0.100$ kWh

$\text{Cost} = 0.100 \times 0.17 = \$0.017$

14.8 Internal Resistance r of a Source of emf

Internal Resistance r and Its Effects

Consider a simple circuit consisting of a cell and a resistor. [The terms cell and battery are used interchangeably here.]



In an ideal circuit,

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

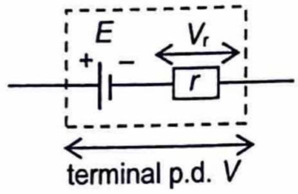
However, **real** cells have internal resistance r. Hence, not all electrical energy generated is available to the external load R. Some of this energy is lost as heat within the cell due to its internal resistance. As a result, the terminal p.d. is not equal to the e.m.f. of the source.

Model of a real battery

A **real** battery can be modelled as follows

- a resistance r, which is
- connected in series to an ideal e.m.f. source

as shown in the dashed box.

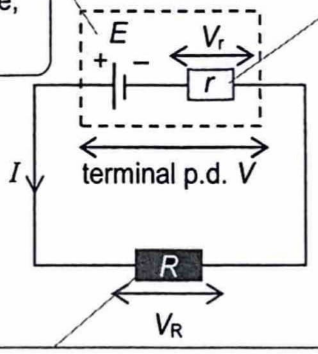


For a circuit with a **battery** of e.m.f. E, an internal resistance r and a terminal p.d. V.

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

By the principle of conservation of energy,
Power **supplied** by source = Power **dissipated** in r and R

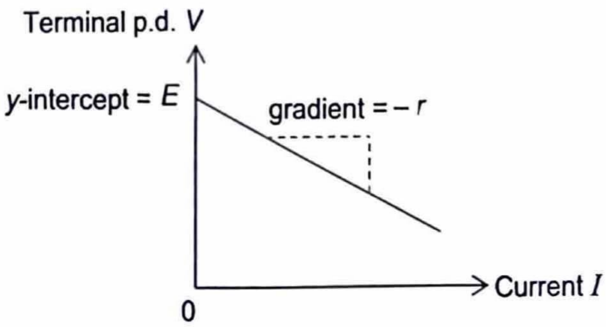
$$P_S = P_r + P_R$$
$$IE = I^2 r + I^2 R$$

Formula

$\boxed{E = I(r+R)}$ OR $\boxed{E = Ir + V_R}$ OR $\boxed{V_R = E - Ir}$

Terminal p.d. $V = V_R = E - Ir$

Plotting the terminal p.d. V against current I



When **no current** flows (i.e. open circuit),

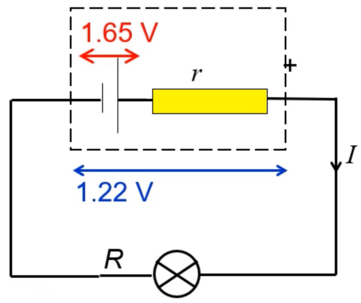
- p.d. across the internal resistance is 0
- hence terminal p.d. $V = V_R =$ e.m.f. E of the source

When a current I flows,

- p.d. across the internal resistance r is Ir
- terminal p.d. $V = V_R = E - Ir$
- hence terminal p.d. decreases by Ir

Example 8 A high-resistance voltmeter reads 1.65 V when connected across a dry-cell in an open circuit and 1.22 V when the same cell is supplying a current of 0.30 A through a lamp. Calculate

(a) the e.m.f. of the cell,
(b) the internal resistance of the cell, and
(c) the resistance of the lamp.



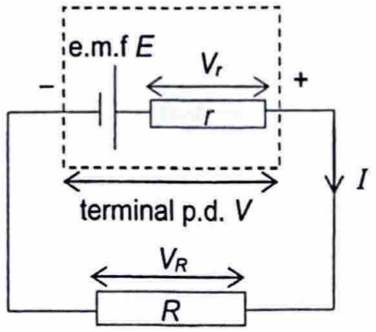
a) e.m.f. E = terminal p.d. when there is no current
$= 1.65$ V

b)
$$V = E - Ir$$
$$1.22 = 1.65 - (0.30)r$$
$$r = 1.43\ \Omega$$

c)
$$V = IR$$
$$1.22 = (0.30)R$$
$$R = 4.07\ \Omega$$

Power Output (Power Transmitted to Load)

A battery with e.m.f. E and internal resistance r is connected to a load of resistance R as shown below.



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

Hence power transferred to the external load R is

$$P_R = I^2R = \left[\frac{E}{(r+R)}\right]^2 R \quad \Rightarrow P_R = \frac{E^2R}{(r+R)^2}$$

Maximum Power Theorem (Maximum Power Transmitted to Load)

To find maximum power delivered to the external load R, differentiating equation above w.r.t R,

$$\frac{dP_R}{dR} = 0$$

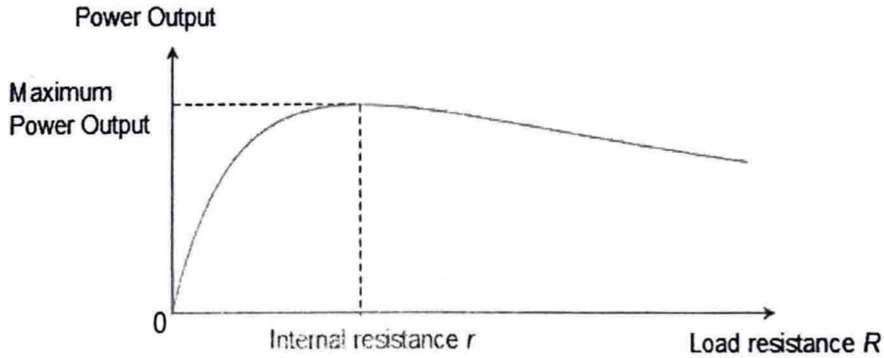
$$\frac{E^2(r+R) - 2E^2R}{(r+R)^3} = 0$$

$$E^2(r+R) - 2E^2R = 0$$

$$(r+R) - 2R = 0$$

$$R = r$$

It can be concluded that a source of e.m.f. delivers the maximum amount of power to an external load when the **resistance of the load is equal to the internal resistance** of the source. This is the maximum power theorem.



Example 9 A cell drives a current of 1.50 A through a 3.08 Ω resistor and 2.00 A through a 2.00 Ω resistor, respectively. Calculate

(a) the e.m.f. of the cell,

(b) the internal resistance of the cell, and

(c) the maximum heating effect it can develop in an external load.

a)
$$E = I_1 r + I_1 R_1 = 1.50r + 4.62 ------(1)$$
$$E = I_2 r + I_2 R_2 = 2.00r + 4.00$$
$$r = \frac{1}{2}E - 2.00 ------(2) \text{ Sub into (1)}$$
$$E = 1.50\left(\frac{1}{2}E - 2.00\right) + 4.62 \quad \Rightarrow \quad E = 6.48 \text{ V}$$

b)
$$r = \frac{1}{2}E - 2.00$$
$$= \frac{1}{2}(6.48) - 2.00 = 1.24\ \Omega$$

c) max heating effect => max power => $r = R = 1.24\ \Omega$
$$E = I(r + R)$$
$$I = \frac{E}{r + R} = \frac{6.48}{1.24 + 1.24} = 2.613 \text{ A}$$
$$P_{\text{max}} = I^2 R = (2.613)^2(1.24) = 8.47 \text{ W}$$

APPENDIX

Colour-code System of a Resistor

A resistor is a circuit element designed to have a known resistance. Resistors are found in almost all electronic devices. The resistance of a resistor is indicated by a colour-code system on the resistor. There are resistors with 4, 5 and 6-band colour codes. For a 4-band colour code, there are usually four coloured stripes on the resistor. The first three coloured stripes indicate the value of its resistance. The first gives the first digit, the second gives the second digit and the third provides the multiplier. The multiplier is the power of ten used to multiply the two-digit number determined from the first two stripes. The table below gives the digits associated with each colour. The fourth stripe on the resistor indicates its tolerance or accuracy. The most commonly used resistors are reliable to within ± 5% of their indicated value.

To read 5 and 6-band colour codes, you may wish to explore the websites below:
http://www.williamson-labs.com/resistors.htm
http://www.the12volt.com/resistors/resistors.asp

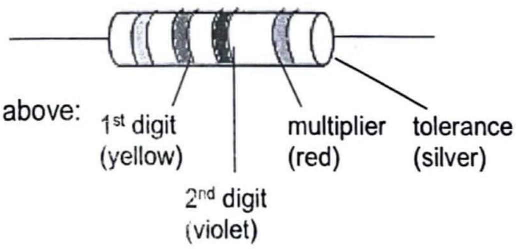
The Resistor Colour Code

Digit	Colour	Multiplier
	Silver	10^{-2} (when used as the third band)
	Gold	10^{-1} (when used as the third band)
0	Black	10^0
1	Brown	10^1
2	Red	10^2
3	Orange	10^3
4	Yellow	10^4
5	Green	10^5
6	Blue	10^6
7	Violet	10^7
8	Grey	10^8
9	White	10^9

Tolerance: (when used as the fourth band)

± 0.5% green band	± 5% gold band
± 1% brown band	± 10% silver band
± 2% red band	± 20% none

A Resistor with 4-Band Colour Code



Referring to the table above:
1st digit – 4
2nd digit – 7

multiplier - 10^2
Resistance of the above resistor: $47 \times 10^2 = 4700\ \Omega$
The figure above shows a **4700 Ω** resistor with a **10% tolerance**

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RAFFLES INSTITUTION
YEAR 5-6 PHYSICS DEPARTMENT

Tutorial 14 CURRENT OF ELECTRICITY

Self-Check Questions

S1 Explain what is meant by an electric current.

S2 State the equation relating charge Q and current I.

S3 State the equation relating current and drift velocity. Explain all symbols used.

S4 Use energy considerations to distinguish between electromotive force (e.m.f.) and potential difference (p.d.).

S5 Define resistance of a circuit component.

S6 State Ohm's Law.

S7 Sketch and explain the I-V characteristics of a metallic conductor at constant temperature, a semiconductor diode and a filament lamp.

S8 Sketch the temperature characteristics of a thermistor.

S9 For a circuit component with potential difference V between its terminals and current I passing through it, what is the electric power P delivered to or extracted from the circuit component? If the component is a resistor of resistance R, what is the electric power delivered to the resistor in terms of R?

S10 How does the internal resistance of a battery affect its terminal p.d. and output power?

S11 State the maximum power transfer theorem.

Self-Practice Questions

SP1 A torch is rated as '2.5 V, 0.030 A'.

(a) How much charge flows through the bulb in 1.0 hour when it is operating at its rated current?

(b) At what rate is electrical energy dissipated in the bulb when it is operating at its rated voltage?

(c) What is its resistance under these operating conditions?

SP2 **(a)** The Earth as a whole carries negative charge. On a day with fine weather, the total charge on the surface of the Earth is 5.5×10^5 C. The Earth revolves around the Sun at a distance of 1.5×10^{11} m once a year. Estimate the average electric current along the orbit.

(b) It is estimated that the average quantity of electric charge transported in a lightning flash is 30 C. If the energy liberated is 2.1×10^{10} J, what is the p.d. involved?

SP3 Distinguish between resistance and resistivity.

SP4 A cylindrical conductor with a length of 2.00 m and a diameter of 0.500 cm is found to carry a current of 4.60 A when a p.d. of 60.0 V is applied between its ends.

(a) What is the resistance of this conductor?

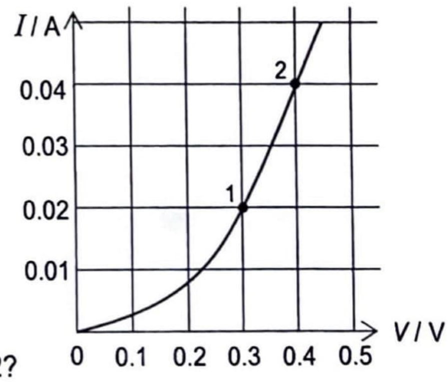
(b) What is the resistivity of the material from which it is made?

SP5 **(a)** A constantan wire of length 15 m is to carry a current of 25 A with a potential drop of no more than 5.0 V along its length. What is the minimum acceptable diameter of this cable?

(b) Calculate the resistance per metre of constantan wire of diameter 0.35 mm. What length of this wire would be needed to make a '12 V, 30 W' heating element?

(resistivity of constantan = 4.8×10^{-7} Ω m)

SP6 An electrical device has the *I*-*V* graph as shown.

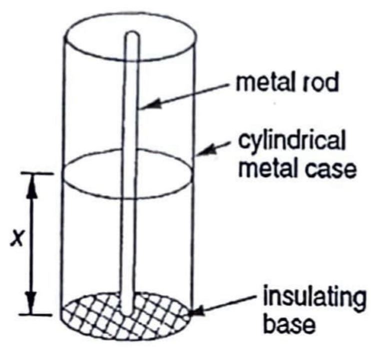


(a) What is the resistance at point 1 and point 2?

(b) What is the power dissipated at point 1 and point 2?

SP7 A conducting liquid fills a cylindrical metal case to a depth x as shown in the diagram.

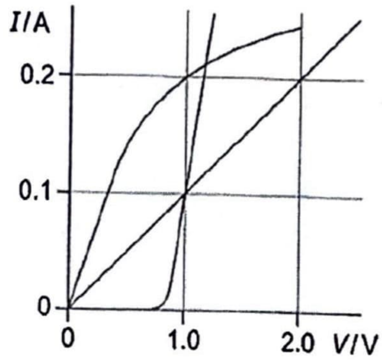
The resistance between the case and the metal rod is



A proportional to x^2.
B proportional to x.
C independent of x.
D inversely proportional to x.
E inversely proportional to x^2.

N88/I/13

SP8 The graph shows the I-V characteristics of three electrical components, a diode, a filament lamp and a resistor, plotted on the same axes.



Which statement is correct?

A The resistance of the diode equals that of the filament lamp at about 1.2 V.

B The resistance of the diode is constant above 0.8 V.

C The resistance of the filament lamp is twice that of the resistor at 1.0 V.

D The resistance of the resistor equals that of the filament lamp when V = 0.8 V.

SP9 For proper balance in some small aircraft, the 12.0 V engine battery must be located in the tail of the plane. The aluminum cables connecting the battery and the motor has a length of 6.10 m, a diameter of 8.25 mm, a resistivity of 2.80×10^{-8} Ω m and it carries a current of 125 A.

(a) What is the potential drop across the aluminum cables?

(b) What is the power dissipated in the cable?

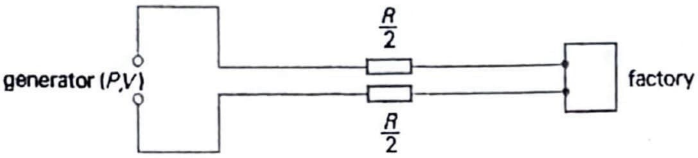
SP10 A cell has e.m.f. 1.5 V and internal resistance 0.5 Ω.

(a) Calculate the power delivered to an external 2.5 Ω resistor.

(b) What is the value of the external resistance if the power delivered is to have a maximum value?

(c) Calculate the terminal p.d. of the cell when maximum power is delivered.

SP11 A generator, with output power P and output voltage V, is connected to a factory by cables of total resistance R.



What is the power input to the factory?

A P

B $P - \left(\frac{P}{V}\right)\frac{R}{2}$

C $P - \left(\frac{P}{V}\right) R$

D $P - \left(\frac{P}{V}\right)^2 \frac{R}{2}$

E $P - \left(\frac{P}{V}\right)^2 R$

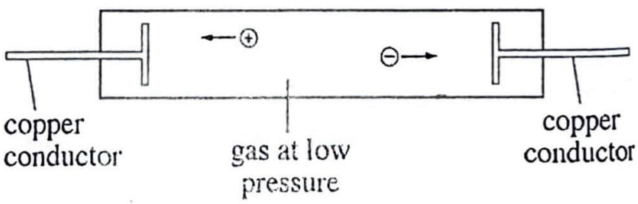
N92/I/14

Self-Practice Answers

SP1	(a) 108 C (b) 0.075 W (c) 83 Ω	**SP2**	(a) 0.017 A (b) 7.0 × 10^8 V
SP4	(a) 13.0 Ω (b) 1.28 × 10^{-4} Ω m	**SP5**	(a) 6.8 x 10^{-3} m, 5.0 Ω m^{-1} (b) 0.96 m
SP6	(a) 15 Ω, 10 Ω (b) 6.0 × 10^{-3} W, 16 × 10^{-3} W	**SP7**	**D**
SP8	**A**	**SP9**	(a) 0.400 V (b) 50.0 W
SP10	(a) 0.63 W (b) R = 0.5 Ω (c) 0.75 V	**SP11**	**E**

Discussion Questions

D1 In a gas, conduction occurs as a result of negative particles flowing one way and positive particles flowing in the opposite direction as shown below.



In this case, the copper conductors to the gas carry a current of 0.28 mA. The number of negative particles passing any point in the gas per unit time is 1.56 × 10^{15} s^{-1} and the charge on each negative particle is −1.60 × 10^{-19} C.

Calculate

(a) the negative charge flowing past any point in the gas per second,

(b) the positive charge flowing past any point in the gas per second,

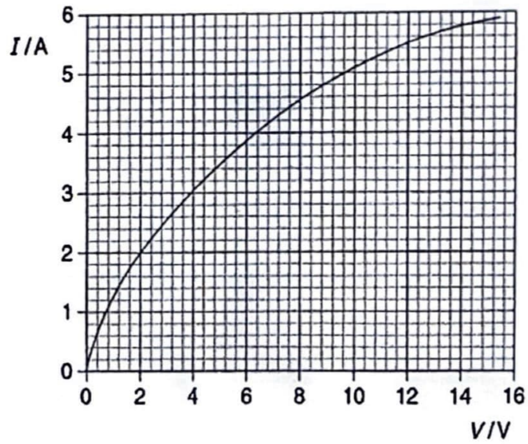
(c) the number of positively charged particles passing any point in the gas per second, given that the charge on each positive particle is +3.20 × 10^{-19} C.

(d) By considering the significant figures available, explain why your answers to **(b)** and **(c)** are unreliable.

[N99/3/5(c), (d)]

D2 A copper wire of diameter 1.0 mm carries a current of 1.0 A. Given that each copper atom contributes one free electron, estimate the drift velocity of the free electrons in the wire.
(density of copper = 8960 kg m^{-3}, mass of each copper atom = 1.06×10^{-25} kg)

D3 **(a)** The *I*-*V* characteristics of a 12 V car headlamp is drawn in the following figure. Only positive values of *V* and *I* are shown.



(i) State why the graph stops at $V = 15.4$ V.

(ii) Deduce the resistance of the headlamp at 4.0V and at 12.0V.

(iii) Explain why the resistance at either of these voltages values is not the reciprocal of the gradient of the graph at the same voltage values.

(b) The filament of a lamp could be manufactured from a straight piece of tungsten wire of diameter 0.084mm.

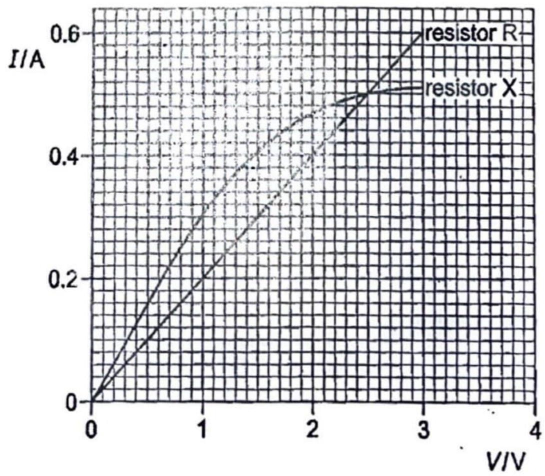
(i) Calculate the length of wire required of a resistance of 0.40Ω when the wire is at room temperature. The resistivity of tungsten at room temperature is 5.5×10^{-8}Ω m.

(ii) Explain why this straight length of wire is impractical.

(iii) Suggest two ways of making a filament wire more practical.

[H1 N2011/2/7(b)]

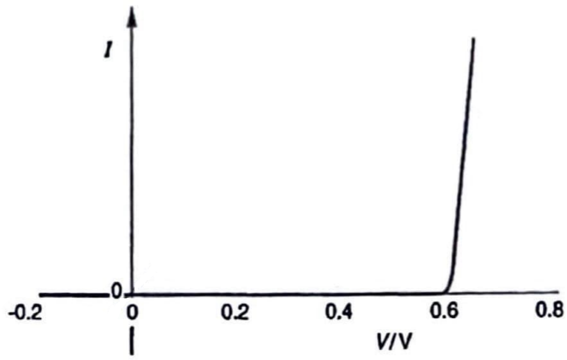
D4 The graph below shows the *I*-*V* characteristics of two resistors R and X.



(a) The resistors R and X are connected in series with a cell of negligible internal resistance. The current in the circuit is 0.2 A. Calculate the e.m.f. of the cell.

(b) Estimate the new current flowing through the cell if its e.m.f. is doubled.

D5 **(a)** The following figure shows the *I*-*V* characteristic of a particular semiconductor diode.



(i) Describe how the resistance of this diode depends on the potential difference *V* across it.

(ii) On the figure above, sketch the *I*-*V* characteristics of a metal conductor at constant temperature.

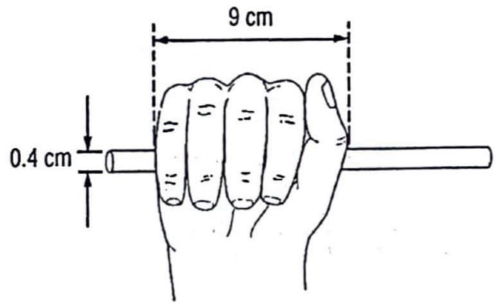
(b) A resistance wire of length *L* and cross-sectional *A* has a resistance *R*. The resistance wire is fixed between two supports. The length of the resistance wire increases when the two supports move apart. The volume of the wire and its resistivity both remain constant.

(i) Show that the resistance of the wire is directly proportional to the square of its length.

(ii) The length of the resistance wire increases by 5.2%. Calculate the ratio of final resistance to initial resistance.

[H1 N2007/2/2]

D6 The resistivity of the human body is low compared with the resistivity of skin, which is about $3.0 \times 10^4\ \Omega$ m for dry skin.



(a) For a layer of dry skin 1.0 mm thick, determine the resistance of a 1.0 cm^2 area of skin.

(b) A person, who is well earthed, accidentally grabs a wire of diameter 0.40 cm at a potential of 50 V. His hand makes contact with the whole circumference of the wire over a distance of 9.0 cm as shown above. The average thickness of the skin of his hand is 1.0 mm. Estimate the current through the person.

(c) Discuss **two** factors, referred to above, which affect the magnitude of the current and hence affect the possible danger from electric shock.

(d) One obvious safety precaution is to keep live wires well insulated. What other safety precautions do you suggest?

[N00/3/4(e)]

D7 A battery is connected in series with a 2.0 Ω resistor and a switch S. A high resistance voltmeter is connected in parallel to the battery. The voltmeter reads 12.5 V when the switch is open, but 8.1 V when the switch is closed. What is the internal resistance of the battery?

D8 An electric utility company supplies a customer's house from the main power lines of 120 V with two copper wires, each of which is 50.0 m long and has a resistance of 0.108 Ω per 300 m.

(a) Find the voltage at the customer's house for a load current of 110 A.

(b) For the load in **(a)**, find

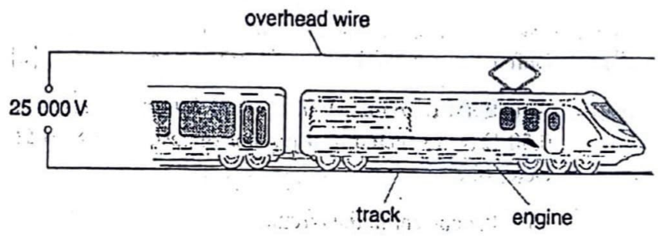
(i) the power that the customer is receiving and

(ii) the power lost in the copper wires.

(iii) the efficiency of transmission.

(c) If 1 kWh of electrical energy costs $0.17, how much will the customer need to pay if he uses electricity for 3 hours?

D9 The figure shows the arrangement for supplying power to an engine. A 25 kV supply is used and the return current from the engine returns through the track. The resistance per kilometre of the overhead wire is 0.344 Ω and the resistance of the track can be neglected.



(a) Consider first when the engine is close to the power supply and require 6700 kW of power. Calculate the current which is needed.

When the engine is 30 km from the power supply, it is supplied with a current of 241 A. Calculate

(b) **(i)** the resistance of the overhead wire between the power supply and the engine.

(ii) the potential difference across the engine

(iii) the power supplied to the engine

(iv) the fraction of the power supplied which is used by the engine

(c) Explain the following facts about the supply to the engine.

(i) A railway employee who touches the track through which there is a current of 241 A does not get an electric shock.

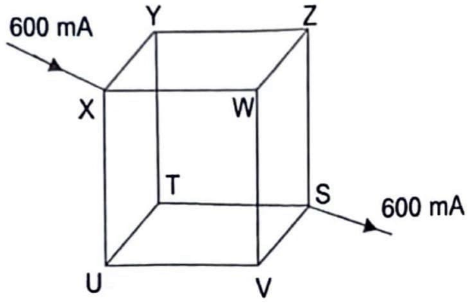
(ii) For constant power transmitted, a high voltage supply is essential for a railway system such as this.

(iii) A different current is needed when the train is climbing a hill from that required when travelling at the same speed on the flat.

[N98/3/4(d), (e)]

Challenging Questions

C1 A resistance network is formed by connecting twelve identical constantan wires, each of length 20 mm and cross-sectional area 0.66 mm², as the edges of a cube as shown in the figure on the right.



(a) Find the resistance of *one* of the constantan wires, given that the resistivity of constantan is 4.9×10^{-7} Ω m.

(b) A current of 600 mA enters at the corner X and leaves at the diagonally opposite corner S. By considering the symmetry of the cube, find the currents in each of the wires.

(c) The potential difference between X and S is the algebraic sum of the potential differences across each of the wires making up a continuous path between X and S. Hence, find the resistance of the network between X and S.

C2 A thin layer of copper is deposited uniformly on the surface of an iron wire of radius 0.50 mm. Calculate the thickness of copper required to reduce the resistance between the ends of the copper-plated wire to 75 % of the resistance of the bare iron wire.

(Resistivity of iron = 8.9×10^{-8} Ω m, resistivity of copper = 1.6×10^{-8} Ω m)

C3 An electrical transmission line connects a generator to a load. The line has resistance *X*, giving rise to power loss in the line. The load resistance is *R*.

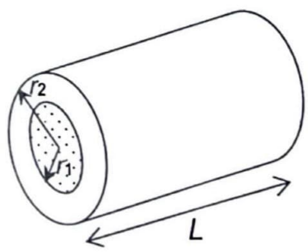
(a) Show that, for a given power *P* delivered by the generator, the power loss in the line is inversely proportional to V^2, where *V* is the output voltage of the generator.

(b) This system is to transmit power of 200 kW from the generator. The line resistance is 0.60 Ω. It is required that the power loss in the line should not exceed 0.015 % of the total power. Find the minimum output voltage to achieve this.

C4 A resistor is made from a material of resistivity ρ. It is formed in the shape of a hollow cylinder with inner radius r_1, outer radius r_2 and length L.

Show that the resistor's resistance to current flow perpendicular to the cylinder's axis, in the radial direction, is given by

$$R = \frac{\rho}{2\pi L}\ln\frac{r_2}{r_1}.$$



Discussion Answers

D1	(a) 0.250×10^{-3} C s^{-1} (b) 0.03×10^{-3} C s^{-1} (c) 9.4×10^{13} s^{-1}	**D2**	0.094 mm s^{-1}
D3	(a)(ii) 1.33Ω , 2.18Ω (b)(i) 0.040m	**D4**	(a) 1.65 V (b) 0.38A
D5	(b)(ii) 1.11	**D6**	(a) 3.0×10^{5} Ω (b) 1.88 mA
D7	1.1 Ω	**D8**	(a)116 V (b)(i) 12.8 kW (ii) 436 W (iii) 97 % (c) \$6.53
D9	(a) 268 A (b)(i) 10.3 Ω (ii) 22500 V (iii) 5430 kW (iv) 0.900	**C1**	(a) 1.5×10^{-2} Ω (b) 200 mA, 100 mA (c) 7.5×10^{-3} V, 1.3×10^{-2} Ω
C2	0.015 mm	**C3**	(b) 2.83×10^{4} V

Suggested Solutions to Self-Check Questions

S1 Electric current is defined as the rate of flow of charge.

S2 $Q = It$, where t is the time duration.

S3 $I = nAv_Dq$, where I is the current, n is the number density of charges, A is the cross-sectional area perpendicular to the direction of the current, v_D is the drift velocity and q is the charge carried by each charge carrier.

S4 a) The **potential difference** between two points in a circuit is defined as the amount of electrical energy per unit charge that is converted *to* other forms of energy when charge passes from one point to the other.

b) The **electromotive force of a source** is defined as the amount of electrical energy per unit charge that is converted *from* other forms of energy when charge passes through the source.

Or:

p.d. across an external load, V	e.m.f. of a source, E
$V = \dfrac{W}{Q}$	$E = \dfrac{W}{Q}$
W is the energy converted **from electrical energy** to other forms	W is the energy converted **from other forms** to electrical energy

S5 Resistance of a circuit component is the ratio of the potential difference across the component to the current passing through it.

S6 Ohm's Law states that the current through a conductor is proportional to the potential difference across it provided there is no change in the physical conditions (e.g. temperature) of the conductor.

Note: Ohm's Law deals with proportionality. $R = \dfrac{V}{I}$ defines resistance R for any conductor, whether or not it obeys Ohm's law. Only when R is constant can we say that the conductor obeys Ohm's law.

S7 Refer to lecture notes.

S8 Refer to lecture notes.

S9 $P = IV$, $P = I^2R$ or $P = V^2/R$.

S10 When a current I flows through the battery, there is a potential drop of Ir across its internal resistance r. Hence, the p.d. across the battery (terminal p.d.) is

$$V = E - Ir$$

Multiplying this equation by I, we find

$$P = IV = IE - I^2r$$

IE is the power supplied by the source (rate of conversion of non-electrical energy to electrical energy within the source). I^2r is the power dissipated in the internal resistance of the source. The difference P is the net electrical power output of the source.

S11 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.

Suggested Solutions to Self-Practice Questions

SP1 **(a)** $Q = It = 0.03(60 \times 60) = 108 \text{ C}$

(b) $P = IV = 0.030(2.5) = 0.075 \text{ W}$ OR $W = VQ = 2.5(108) = 270 \text{ J}$

$$P = \frac{270}{60 \times 60} = 0.075 \text{ W}$$

(c) $R = \dfrac{V}{I} = \dfrac{2.5}{0.03} = 83 \,\Omega$

SP2 **(a)** In one year, a total of 5.5×10^5 C of charge passes a point in the orbit.

$$I = \frac{Q}{t} = \frac{5.5 \times 10^5}{365 \times 24 \times 60 \times 60} = 0.017 \text{ A}$$

(b) $V = \dfrac{W}{Q} = \dfrac{2.1 \times 10^{10}}{30} = 7.0 \times 10^8 \text{ V}$

SP3 The resistance of a conductor is the ratio of the potential difference across it to the current flowing through it. It is not constant for a given material, at a fixed temperature, but depends on its shape and size.

S.I. unit: ohm, Ω

The resistivity of a material is numerically equal to the resistance between opposite faces of a cube of the material of unit length and unit cross-sectional area. It is constant for a given material, at a fixed temperature, regardless of its shape and size.

S.I. unit: ohm-metre, Ω m

SP4 **(a)** $R = \dfrac{V}{I} = \dfrac{60.0}{4.60} = 13.0\ \Omega$

(b) $A = \pi r^2 = \pi\left(\dfrac{0.500\times10^{-2}}{2}\right)^2$

$$\rho = \frac{RA}{l} = \frac{13.0\pi\times\left(\dfrac{0.500\times10^{-2}}{2}\right)^2}{2.00} = 1.28\times10^{-4}\ \Omega\ \text{m}$$

SP5 **(a)** $R_{max} = \dfrac{V_{max}}{I} = \dfrac{5.0}{25} = 0.20\ \Omega$

$$R = \rho\frac{l}{A} = \rho\frac{l}{\pi\left(\dfrac{d}{2}\right)^2} = \rho\frac{4l}{\pi d^2}$$

$$d_{min} = \sqrt{\rho\frac{4l}{\pi R_{max}}} = \sqrt{\left(4.8\times10^{-7}\right)\left(\frac{4\times15}{\pi\times0.20}\right)} = 6.77\times10^{-3}\ \text{m}$$

(b) $R = \rho\dfrac{l}{A}$

Resistance per metre $= \dfrac{R}{l} = \dfrac{\rho}{A} = \dfrac{4.8\times10^{-7}}{\pi\left(\dfrac{d}{2}\right)^2} = \dfrac{4\left(4.8\times10^{-7}\right)}{\pi\left(0.35\times10^{-3}\right)^2} = 5.0\ \Omega\ \text{m}^{-1}$

Resistance of filament, $R = V^2 / P = 12^2 / 30 = 4.8\ \Omega$

length of wire, $l = 4.8 / 5.0 = 0.96$ m

SP6 **(a)** Point 1: $R = \dfrac{V}{I} = \dfrac{0.3}{0.02} = 15\ \Omega$

Point 2: $R = \dfrac{V}{I} = \dfrac{0.4}{0.04} = 10\ \Omega$

(b) Point 1: $P = IV = 0.02\ (0.3) = 6.0 \times 10^{-3}$ W

Point 2: $P = IV = 0.04\ (0.4) = 16 \times 10^{-3}$ W

SP7 Current is travelling radially to or from the centre rod.

Length through which current flows in the radial direction = r

Area A normal to current flow = cylindrical surface area = $2\pi rx$

Since $R = \rho l/A = \rho r/2\pi rx$ = constant/x $\Rightarrow$ resistance is inversely proportional to x

Ans: D

SP8 curved graph (as V increases I increases at a decreasing rate) – filament lamp

straight line – resistor

curved then straight – diode

option A: true, the 2 graphs intersect at that point

option B: not true, the ratio of V/I is not constant

option C: not true, resistance of filament lamp is half that of the resistor

option D: not true, the 2 graphs DO NOT intersect at that point.

Ans: A

SP9 **(a)** $R = \rho\frac{l}{A} = \left(2.80\times10^{-8}\right)\left(6.10\Big/\pi\left(\frac{8.25\times10^{-3}}{2}\right)^2\right) = 3.20\times10^{-3}\ \Omega$

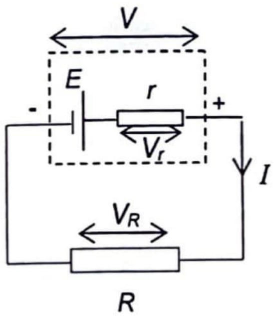
$V = RI = (3.20 \times 10^{-3})\ (125) = 0.400\ \text{V}$

(b) $P = IV = (125)\ (0.40) = 50.0\ \text{W}$

OR $P = I^2R = (125)^2\ (3.20 \times 10^{-3}) = 50.0\ \text{W}$

OR $P = V^2/R = (0.40)^2 / (3.20 \times 10^{-3}) = 50.0\ \text{W}$

SP10 $E = 1.5\ \text{V}$, $r = 0.5\ \Omega$, $R = 2.5\ \Omega$



$E = V_r + V_R = Ir + IR = I(r + R)$

$$I = \frac{E}{r+R}$$

(a) $I = \frac{1.5}{0.5+2.5} = 0.5\ \text{A}$

Power delivered to $R = I^2R = (0.5)^2\ (2.5) = 0.63\ \text{W}$

(b) For maximum power, $R = r = 0.5\ \Omega$

(c) $I = \frac{1.5}{2\times0.5} = 1.5\ A$

Terminal p.d., $V = E - Ir = 1.5 - 1.5\ (0.5) = 0.75\ \text{V}$

SP11 Current through circuit $I = P/V$

$P_{gen} = P_{cable} + P_{factory}$

$P_{factory} = P_{gen} - P_{cable} = P - I^2R = P - (P/V)^2R$

Ans: E