Developed exclusively with the Caribbean Examinations Council (CXC®), this study guide will provide candidates in and out of school with additional support to maximise their performance in CAPE® Physics Unit 2.

Written by an experienced team comprising teachers and experts in the CAPE® Physics Unit 2 syllabus and examination, this study guide covers the elements of the syllabus that you must know in an easy-to-use double-page format. Each topic begins with the key learning outcomes from the syllabus and contains a range of features designed to enhance your study of the subject, such as:

- **Examination-style practice questions** to build confidence ahead of your examinations
- **Exam tips** with useful advice to help you succeed in your examinations
- **Definitions** providing succinct explanations of essential terms.

This comprehensive self-study package includes a fully interactive CD, incorporating multiple-choice questions and sample examination answers with accompanying examiner feedback, to build your skills and confidence as you prepare for the CAPE® Physics Unit 2 examination.

The Caribbean Examinations Council (CXC®) has worked exclusively with Nelson Thornes to produce a series of Study Guides across a wide range of subjects at CCSLC®, CSEC® and CAPE®. Developed by expert teachers and resource persons, these Study Guides have been designed to help students reach their full potential as they study their CXC® programme.
Introduction

This Study Guide has been developed exclusively with the Caribbean Examinations Council (CXC®) to be used as an additional resource by candidates, both in and out of school, following the Caribbean Advanced Proficiency Examination (CAPE®) programme.

It has been prepared by a team with expertise in the CAPE® syllabus, teaching and examination. The contents are designed to support learning by providing tools to help you achieve your best in CAPE® Physics and the features included make it easier for you to master the key concepts and requirements of the syllabus. Do remember to refer to your syllabus for full guidance on the course requirements and examination format!

Inside this Study Guide is an interactive CD which includes electronic activities to assist you in developing good examination techniques:

- **On Your Marks** activities provide sample examination-style short answer and essay type questions, with example candidate answers and feedback from an examiner to show where answers could be improved. These activities will build your understanding, skill level and confidence in answering examination questions.

- **Test Yourself** activities are specifically designed to provide experience of multiple-choice examination questions and helpful feedback will refer you to sections inside the study guide so that you can revise problem areas.

- **Answers** are included on the CD for multiple-choice questions and questions that require calculations, so that you can check your own work as you proceed.

This unique combination of focused syllabus content and interactive examination practice will provide you with invaluable support to help you reach your full potential in CAPE® Physics.
Learning outcomes

On completion of this section, you should be able to:
- state that there are two types of charges
- describe and explain charging by friction and induction
- show that like charges repel and unlike charges attract
- distinguish between conductors and insulators.

Charging objects

Lightning is an example of an effect of static electricity. Clouds become charged as they move through the atmosphere. This charge is able to move to other clouds or to objects on the surface of the Earth such as trees or tall buildings. In order to explain this phenomenon, you must first understand how objects become charged.

Charging by friction

A polythene rod is rubbed with a piece of wool and suspended from an insulating thread so that it is free to move. Another polythene rod is rubbed with a piece of wool and placed close to the suspended rod. The suspended rod is repelled.

When a perspex rod is rubbed with a piece of wool it attracts the suspended polythene rod.

Experiments of this nature have shown that:
- there are two types of charge
- similarly charged objects repel each other
- objects that have unlike charges attract each other.

When electrostatic experiments were first conducted, it was arbitrarily decided that glass acquires a positive charge when rubbed with silk and ebonite (a type of hard rubber) acquires a negative charge when rubbed with fur. This convention was made up long before the existence of electrons became known.

It is important to note that charge is not created by the rubbing action. When the polythene rod was rubbed with the piece of wool, electrons were transferred from the surface of the wool to the surface of the polythene rod. The polythene rod acquired a negative charge. At the same time the piece of wool acquired an equal positive charge, because it lost some electrons. In this process, charge is conserved.

To summarise, polythene and ebonite acquire a negative charge when rubbed with wool. Perspex and glass acquire a positive charge when rubbed with wool.

![Electrons transferred from the woollen cloth to the polythene.](image)

Figure 1.1.3 Explaining charging by friction
Charging by induction

An uncharged object can be charged by a charged object by a process called induction. A negatively charged rod is brought close to an uncharged metal sphere. The negatively charged rod causes the electrons in the uncharged metal sphere to move to one side. The metal sphere is then earthed by briefly touching it and the rod is taken away. The metal sphere has then become positively charged.

![Diagram of charging by induction](image)

**Figure 1.1.4 Charging by induction**

Conductors and insulators

Metals are very good conductors of electricity. In a metal atom, the electrons that orbit the nucleus are situated in ‘shells’. The electrons in the innermost shells are held tightly by the nucleus. In the outermost shells, the electrons are held less tightly by the nucleus. These electrons are able to escape the electrostatic force of attraction of the nucleus. These electrons are free to move throughout the metal structure. Since these electrons are free to move, they are said to be delocalised. Each electron has a tiny charge on it. The movement of charge constitutes an electric current. It is because of a high concentration of free, mobile electrons that metals are excellent conductors of electricity. Copper, silver and iron are good conductors of electricity. Graphite is an example of a non-metal that is a conductor of electricity.

Some materials are poor conductors of electricity. These materials are called insulators. In these types of materials the type of bonding found in the structure is different from that of a metal. All the electrons are held tightly in the bonds throughout the structure. This means that there are no free mobile electrons to allow for electrical conduction to take place. Plastic and rubber are good insulators.

Materials that are neither good conductors nor good insulators are called semiconductors.

**Key points**

- There are two types of charge: positive and negative charge.
- Objects can be charged by friction or by induction.
- Charge is always conserved when an object is charged.
- Like charges repel.
- Unlike charges attract.
- Materials that conduct electricity are called conductors.
- Materials that are poor conductors of electricity are called insulators.
Applications of electrostatics

Learning outcomes

On completion of this section, you should be able to:

- describe practical applications of electrostatic phenomena
- appreciate the potential hazards associated with charging by friction.

Practical applications of electrostatics

Agricultural spraying

There are many problems associated with cultivating agricultural land. One such problem is pest control. Pests can be very harmful to development of the plants. They feed on the leaves of plants, usually living on the underside of the leaves. This makes spraying with pesticides a tricky process. A technique has been developed where the nozzle of the spray is connected to a high voltage supply. This high voltage supply has two effects. It charges the spray droplets positively and induces an opposite charge on the ground and the plants. This causes the spray droplets to be attracted to both sides of the leaves. This technique also prevents wastage during the spraying process.

Dust extraction

Dust particles may be extracted from the flue gases released by industrial chimneys, using the electric field that exists between a wire and a metal cylinder.

![Electrostatic dust extraction](image)

The inner wall of the chimney is fitted with a cylindrical piece of metal. A series of wires at high negative voltages are mounted inside the cylinder. A large electric field exists between the wires and the cylinder. The electric field removes electrons from some of the air molecules, thus forming ions. Free electrons in the air close to the wire are accelerated away. Electrons and negative ions in the air become attached to the dust particles. The charged dust particles are then attracted to the inner walls of the cylinder. Hammers are used to strike the cylinder to dislodge dust particles, which then fall into the traps at the bottom of the chimney.

Photocopiers and laser printers

Photocopiers use the principle of electrostatics to copy documents. A light-sensitive cylindrical drum is charged positively by a charged grid. An image of the document being copied is projected on to the drum. The areas on the drum exposed to light lose their positive charge.
A negatively charged powder, called the toner, is dusted over the drum. The toner is attracted to the positively charged image. A sheet of paper then receives a positive charge as it passes over the grid. The positively charged paper attracts toner from the drum and an image is formed on it. The image is made permanent by warming the final product.

A laser printer operates using a similar principle. When the printer receives a digital version of the document to be printed, a laser uses a series of mirrors and lenses to focus it on the light-sensitive cylindrical drum. The image to be printed is written on the drum by the laser.

**Electrostatic paint spraying**

Most car manufacturers use electrostatics to paint their vehicles. As the paint leaves the nozzle of the sprayer, the droplets are given a charge. Since all the droplets have the same charge, they repel each other so that the paint spreads out to form a large even cloud. The body of the car is charged with an equal and opposite charge. The result is that the paint sticks to the surface of the car tightly and less paint is wasted in the process.

**Hazards of static electricity**

Static electricity can be very hazardous. There is always a danger of electric shock from charged objects. For example, our bodies may become charged by friction. Then touching a metal door handle causes the charge to flow to the handle. The flow of charge results in an electric current and you experience an electric shock. It is possible to see and hear a spark as you touch the door handle. Sometimes, it is possible to be charged up to many kilovolts.

Since there is always a danger of a spark being produced by electrostatics, great care must be taken when refuelling aircraft. A spark can ignite the fuel causing a dangerous explosion. A conducting cable is connected between the aircraft and the fuel tanker. This ensures that the aircraft and the fuel tanker are at the same electric potential. This ensures that no spark arises.

In thunderstorms, clouds are charged as they move through the atmosphere. These clouds have huge amounts of charge stored in them. When charge flows between clouds or towards tall buildings and trees, lightning is seen. Very large currents flow during this process. Lightning has been known to start fires, damage buildings and even kill people by electrocution.

A commonly used technique to protect buildings from lightning is to use lightning rods. A lightning rod takes the form of a thick piece of copper strip fixed to an outside wall reaching above the highest part of the building. The part of the rod above the highest part of the building consists of several sharp spikes. The other end of the copper strip is buried in the earth below. When lightning strikes, it usually strikes the highest point of a building and the current travels through the path of least resistance towards the earth. Since the lightning conductor is fixed to the ground it is effectively earthed. When a charged cloud passes by the building, a large electric field is set up between the cloud and the spikes of the lightning rod. This large electric field causes the air molecules to ionise. Electrons are stripped from the air molecules and ions are produced. The air breaks down and begins to conduct electricity. The electric current flows harmlessly through the lightning conductor towards the earth, without damaging the building.

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**Key points**

- Electrostatics is used in electrostatic crop spraying, electrostatic paint spraying, dust extraction, photocopiers and laser printers.
- Charging by friction can create problems, but there are ways to reduce the effects.
2.1 Electric current and potential difference

**Learning outcomes**

On completion of this section, you should be able to:
- understand that an electric current is the flow of charge
- define charge and the coulomb
- recall and use $Q = It$
- define potential difference and the volt
- recall and use $V = \frac{W}{Q}$

**Definition**

An electric current is the rate of flow of charge.

**Equation**

$Q = It$

$Q$ – charge/C

$I$ – current/A

$t$ – time/s

**Definition**

1 coulomb is the quantity of charge that passes through any section of a conductor in 1 second when a current of 1 ampere is flowing.

$1 \text{C} = 1 \text{As}$

**Electric current and charge**

Metals are good conductors of electricity. In a metal there are many atoms present. The outer shell electrons of the metal atoms are not tightly bound and are free to move throughout the lattice. Each electron carries a tiny amount of charge. When these charged particles (electrons) move in a particular direction, an **electric current** is produced. An electric current is the rate of flow of charged particles. The SI unit of electric current is the ampere (A).

When a salt such as sodium chloride is dissolved in water, sodium and chloride ions are produced. The ions present in the solution are charged. Therefore, a solution of sodium chloride will allow an electric current to flow through it.

Charged particles can have either a negative or a positive charge. The faster the charged particles move the greater the electric current.

The SI unit of charge is the **coulomb** [C]. An electron has a charge of $1.6 \times 10^{-19}$ C.

In order for the electrons in a metal to flow, energy must be supplied. In a simple circuit, an electric cell can be used to provide the energy needed to move the free electrons in the metal. The cell produces energy because of the chemical reactions taking place inside it.

**Definition**

In Figure 2.1.1 the electrons are flowing through the metal from right to left. The conventional electric current, however, is defined as flowing in the opposite direction. In an electrical circuit we think of the electric current as flowing from the positive terminal of the cell to the negative terminal. It is important to remember that if a stream of electrons is flowing in one direction, it can be thought of as the conventional electric current flowing in the opposite direction. If a stream of positive ions is flowing in one direction, the electric current will be flowing in that same direction.

Electrical currents are measured using an **ammeter**. In order to measure the electric current flowing through a component in a circuit, an ammeter is connected as shown in Figure 2.1.2. The ammeter is connected in series with the component. An ideal ammeter has zero resistance.

**Example**

In a cathode ray tube, there is a current of $160 \mu\text{A}$ in the vacuum between the anode and cathode. Calculate:

a the time taken for a charge of $2.5 \text{C}$ to be transferred between the cathode and anode

**Figure 2.1.1 Diagram showing the direction of electron flow in a metal**

**Figure 2.1.2 Measuring an electric current**
b the number of electrons emitted per second from the cathode.
(Charge on one electron \( e = -1.6 \times 10^{-19} \text{C} \))

\[
\begin{align*}
\text{a} & \quad t = \frac{Q}{I} = \frac{2.5 \times 10^{-6}}{160 \times 10^{-6}} = 1.56 \times 10^4 \text{s} \\
\text{b} & \quad \text{Charge on one electron} = e = -1.6 \times 10^{-19} \text{C} \\
& \quad \text{Charge flowing per second} = 160 \mu\text{C} \\
& \quad \text{Number of electrons emitted per second} = \frac{160 \times 10^{-6}}{1.6 \times 10^{-19}} = 1 \times 10^{15}
\end{align*}
\]

**Potential difference**

Whenever the term unit positive charge is used, it refers to +1 C of charge. Energy is required to move charge around an electrical circuit. A cell is usually required to power an electrical circuit. The cell converts chemical energy into electrical energy. When charge passes through components in a circuit, energy is converted from electrical to other forms of energy. In a filament lamp, electrical energy is converted into light and thermal energy. In the case of a resistor, electrical energy is converted into thermal energy.

An electric current flows from one point to another because of a difference in electric potential between the two points. The potential at a point in an electric field is defined as the work done in moving unit positive charge from infinity to that point. The SI unit of potential is the volt (V).

In the circuit in Figure 2.1.3 a cell is being used to provide a current \( I \) through resistors \( R_1 \) and \( R_2 \). Figure 2.1.4 shows the variation of electric potential around the circuit relative to point F.

Electric potential cannot be measured directly. The difference in electric potential can, however, be measured. A voltmeter is used to measure potential difference. A voltmeter is connected in parallel with the component whose potential difference is being measured. An ideal voltmeter has an infinite resistance.

As charge passes between the two points, energy is converted from electrical to some other form. In the case of a resistor, electrical energy is converted into thermal energy. The resistor gets warm as charge flows through it. In the case of a filament lamp, electrical energy is converted into light and thermal energy.

The unit of potential difference is the volt (V).

1 volt is defined as the potential difference between two points in a circuit when 1 joule of energy is converted when 1 coulomb of charge flows between the two points.

\[
1 \text{V} = 1 \text{J C}^{-1}
\]

**Key points**

- An electric current is the rate of flow of charge.
- 1 coulomb is the quantity of charge that passes through any section of a conductor in 1 second when a current of 1 ampere is flowing.
- The potential at a point is defined as the work done in moving unit positive charge from infinity to that point.
- The potential difference \( V \) between two points in a circuit is the work done (energy converted from electrical energy to other forms of energy) in moving unit positive charge from one point to the other.
- 1 volt is defined as the potential difference between two points in a circuit when 1 joule of energy is converted when 1 coulomb of charge flows between the two points.

\[
V = \frac{W}{Q}
\]

\[
V \quad \text{potential difference/V} \\
W \quad \text{work done/J} \\
Q \quad \text{charge/C}
\]
Learning outcomes

On completion of this section, you should be able to:

- explain the term drift velocity
- derive an expression for drift velocity
- recall and use \( P = IV \), \( P = I^2R \) and \( P = V^2/R \)
- recall the symbols for commonly used circuit components.

Drift velocity

When there is no current flowing in a metal, the electrons are moving about rapidly with a range of speeds, in random directions. When a potential difference is applied across a metal an electric field is set up. The free electrons begin moving under the influence of the electric field. As the free electrons accelerate they collide continuously with metal ions. This movement of the electrons is superimposed on the random motion. The drift velocity is the mean value of the velocity of the electrons in a conductor when an electric field is applied.

Consider a section of a metallic conductor of length \( L \) and cross-sectional area \( A \). Let:

\[
I = \text{current flowing in the conductor}/A \\
n = \text{the number of free electrons per unit volume}/m^3 \\
e = \text{charge on each electron}/C \\
v = \text{the mean drift velocity of the electrons}/m\,s^{-1} \\
\text{Volume of section} = AL \\
\text{Number of electrons in the section} = nAL \\
\text{Total amount of charge flowing}
\]

Time taken for electrons to travel from one end of the section to the next \( = \frac{L}{v} \)

Electric current \( I = \frac{Q}{t} = \frac{nALe}{L/v} \)

\[
I = nevA
\]

Example

A potential difference is applied across a piece of copper wire with cross-sectional area of \( 1.3 \times 10^{-6} \) m\(^2\). The current flowing through it is 1.2 mA. The concentration of free electrons in copper is \( 8.7 \times 10^{28} \) m\(^{-3}\). Calculate the drift velocity of the free electrons in the wire.

Drift velocity \( v = \frac{I}{ne} = \frac{1.2 \times 10^{-3}}{8.7 \times 10^{28} \times 1.3 \times 10^{-6} \times 1.6 \times 10^{-19}} \approx 6.6 \times 10^{-8} \) m/s

In a metal, conduction is due to free electrons. In an electrolyte (e.g. a solution of sodium chloride) the mobile charge carriers are positive and negative ions [Na\(^+\) and Cl\(^-\) in this case]. In a semiconductor, the mobile charge carriers are electrons and ‘holes’.

Example

Suppose a uniform glass tube of cross-sectional area \( A \) contains a salt solution (electrolyte). A current \( I \) flows through the solution. The current is carried equally by positive and negative ions. The charges on the positive and negative ions are \(+2e\) and \(-2e\) respectively. The number of each ion species per unit volume is \( n \). Write down an expression for the current \( I \) flowing through the solution in terms of the drift velocity of charge carriers in the salt solution.
The positive and negative ions flow in opposite directions. Therefore, if the positive ions flow with a drift velocity $v$, the negative ions will flow with a drift velocity $-v$.

Current $I = n(+2e)[v](A) + n(-2e)[-v](A) = 4nevA$

**Energy and power**

Consider a steady current $I$, flowing through a resistor $R$ for a duration of time $t$. As current flows through the resistor it dissipates energy. The energy dissipated is equal to the potential energy lost by the charge as it moves through the potential difference between terminals of the resistor.

From the definition of potential difference

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

where

$W$ is the energy dissipated in a time $t$

$Q$ is the charge that flowed during a time $t$

$V$ is the potential difference across the resistor

The charge that flows during time $t$ is $Q = It$

$$\therefore W = ItV$$

**Power** is defined as the rate at which energy is converted.

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

$$\therefore P = \frac{ItV}{t}$$

$$P = IV$$

The SI unit of power is the **watt** [W].

From the definition of resistance (see 2.3)

$$V = IR$$

$$\therefore P = I(IR) = I^2R$$

Also,

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

**Commonly used circuit symbols**

Figure 2.2.2 shows a list of commonly used electrical circuit symbols that will be encountered in the chapters that follow.

**Key points**

- The drift velocity is the mean value of the velocity of the electrons in a conductor when an electric field is applied.
- Power is the rate at which energy is converted.

**Definition**

1 watt is a rate of conversion of energy of 1 joule per second.

$1W = 1Js^{-1}$
2.3 Resistance

**Learning outcomes**

On completion of this section, you should be able to:

- define resistance and the ohm
- recall and use \( V = IR \)
- sketch \( I-V \) characteristics
- state Ohm’s law
- define resistivity.

**Resistance**

In a metal, there are free electrons throughout the structure. These electrons are free to move within the metal. When a cell is connected across the ends of a piece of metal, the electrons begin moving. The cell provides the necessary energy to allow the electrons to move. As the electrons move through the metal they collide with each other and the metal ions. These collisions restrict the flow of electrons. This property of the metal is known as **electrical resistance**.

The circuit in Figure 2.3.1 is used to determine the resistance of the component X. The component in this case is a resistor. The voltmeter reading gives the potential difference across the resistor. The ammeter reading gives the current flowing through the resistor. The ratio of the potential difference to the current flowing through component X is its resistance.

**Definition**

Resistance (\( R \)) is defined as the ratio of the potential difference (\( V \)) across the conductor to the current (\( I \)) flowing through it.

\[
R = \frac{V}{I}
\]

\( R \) – resistance/\( \Omega \)
\( V \) – potential difference/V
\( I \) – current/A

The SI unit of resistance is the **ohm** (\( \Omega \)).

**Current–voltage graphs**

In the circuit in Figure 2.3.2 a variable resistor is used to adjust the current flowing through the component X.

The variable resistor is adjusted and several values of \( V \) and the corresponding values of \( I \) are recorded. A graph of \( I \) against \( V \) is then plotted to obtain the \( I-V \) characteristic of the component.

Figure 2.3.3 shows the \( I-V \) characteristic for a metallic conductor at constant temperature. The graph is a straight line through the origin. The current \( I \) is directly proportional to the potential difference \( V \). This relationship is known as **Ohm’s law**.

**Definition**

Ohm’s law states that the current flowing through a conductor is directly proportional to the potential difference across it provided that there is no change in the physical conditions of the conductor.

![Figure 2.3.1 Measuring electrical resistance](image)

![Figure 2.3.2 Circuit used to obtain data to plot an \( I-V \) curve](image)

![Figure 2.3.3 \( I-V \) characteristic for an ohmic conductor](image)
A conductor that obeys Ohm’s law is called ‘ohmic’.

The physical conditions could be temperature or mechanical strain.

Figure 2.3.4 shows the $I–V$ characteristic for a filament lamp.

The graph for the filament lamp does not obey Ohm’s law. The resistance of the filament lamp is not constant. It varies with current.

From the $I–V$ characteristics of the filament lamp it can be seen that the resistance of the lamp increases as the voltage increases. As more current flows through the lamp the temperature of the filament increases. The kinetic energy of the atoms inside it increases. The atoms vibrate rapidly about their mean positions. The moving electrons in the filament lamp collide with these vibrating atoms. As a result, the movement of electrons through the filament lamp becomes restricted. This explains why the resistance of the filament lamp increases.

Figure 2.3.5 shows the $I–V$ characteristic for a semiconductor diode.

The $I–V$ graph for the semiconductor diode does not obey Ohm’s law. When the semiconductor diode is connected so that it is reverse-biased (see 8.3) it does not allow any current to flow. The resistance is infinite when it is reverse-biased. This is the reason why the current is zero for negative voltages. If the semiconductor diode is now connected so that it is forward-biased (see 8.3), it begins to allow a current to flow when the voltage is approximately $0.6 \, \text{V}$.

It may be desirable for the resistance of a device to vary with temperature. One such device is a thermistor. There are two kinds of thermistor. There is one type whose resistance decreases exponentially with increasing temperature. These thermistors are said to have a negative temperature coefficient. There is another kind whose resistance increases suddenly at a particular temperature. These thermistors are said to have a positive temperature coefficient.

Figure 2.3.6 shows how the resistance of a thermistor having a negative temperature coefficient varies with temperature.

Thermistors are used as temperature sensors in many electrical devices. They are used in aircraft wings to monitor external temperature.

**Resistivity**

Resistance depends on several factors. It depends on the resistivity of the material, the length of the material, the cross-sectional area of the material and the temperature of the material.

The resistivities of silver and copper are $1.6 \times 10^{-8} \, \Omega \cdot \text{m}$ and $1.7 \times 10^{-8} \, \Omega \cdot \text{m}$ respectively. Copper and silver are good electrical conductors and therefore have low resistivities.

**Key points**

- Resistance ($R$) is defined as the ratio of the potential difference ($V$) across the conductor to the current ($I$) flowing through it.
- 1 ohm is defined as the resistance of a conductor through which a current of 1A flows when there is a potential difference of 1V across it.
- Resistivity ($\rho$) is defined by $R = \frac{\rho L}{A}$.

---

**Definition**

The following equation is used to define the resistivity of a material. The SI unit of resistivity is $\Omega \cdot \text{m}$.

**Equation**

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

- $R$ – resistance/$\Omega$
- $\rho$ – resistivity/$\Omega \cdot \text{m}$
- $L$ – length/m
- $A$ – cross-sectional area/$\text{m}^2$
Electromotive force (e.m.f.) and internal resistance

In an electrical circuit, a source provides the energy required to drive an electric current in the circuit. The source has a positive and a negative terminal. Electrons are forced out of the negative terminal in a closed circuit. Examples of sources include cells, batteries, solar cells and dynamos.

In a cell, chemical energy is converted into electrical energy. The electromotive force (e.m.f.) of a cell is the energy converted from chemical energy to electrical energy per unit charge flowing through the cell. In 2.1, potential difference was defined as energy converted from electrical energy to other forms of energy per unit charge flowing between two points.

Learning outcomes

On completion of this section, you should be able to:

- understand the difference between potential difference and e.m.f.
- understand the concept of internal resistance.

Equation

\[ V = \frac{W}{Q} \]

where

- \( V \) – electromotive force, e.m.f./V
- \( W \) – work done/J
- \( Q \) – charge/C

Exam tip

1. e.m.f. is associated with active devices (e.g. batteries) that produce electrical power.
2. Potential difference is associated with passive devices (e.g. resistors).
3. Potential difference is also associated with electric fields (see 4.1).

The chemicals inside a cell provide a resistance to the flow of current. The resistance that is internal to the cell is called the internal resistance. A cell having an e.m.f. of \( E \) and an internal resistance of \( r \) can be represented as shown in Figure 2.4.1.

Effect of increasing internal resistance

Suppose a cell is connected to an external load \( R \) and supplies a current \( I \) in the circuit as shown in Figure 2.4.2.

The e.m.f. can be written as follows:

\[ E = I \times (R + r) \]

where \( (R + r) \) is the total resistance in the circuit.

Therefore, \( E = IR + Ir \), where \( IR \) is the potential difference across the external load and \( Ir \) is the potential difference across the internal resistance of the cell.

The potential difference across the external load is \( V \).

\[ \therefore \quad E = V + Ir \]

From the last equation, when \( I \) is equal to zero, \( E = V \) [the potential difference between A and B]. Therefore, when \( I \) is equal to zero, the terminal potential difference is equal to the e.m.f. of the cell.

The power dissipated in the external resistor, \( P_R \), is given by:

\[ P_R = I^2R \]

The total power generated by the cell \( P_T \) is given by:

\[ P_T = I^2(R + r) \]
The fraction of the total power dissipated in the external resistor is given by:

\[
\frac{P_R}{P_T} = \frac{I^2 R}{P_T[R + r]}
\]

After prolonged use, the internal resistance of a cell may increase. The increased internal resistance reduces the maximum current that the cell can supply. This reduces the total power \( P_T \). This reduces the fraction of the total power supplied to the resistor \( R \). As a result, the power supplied to \( R \) is reduced.

**Measuring e.m.f. and internal resistance**

The circuit diagram in Figure 2.4.3 shows the circuit that can be used to measure the e.m.f. and internal resistance of a cell experimentally.

The resistance \( R \) is adjusted so that a series of readings \((V)\) of the voltmeter \( V \) and the corresponding readings \((I)\) of the ammeter \( A \) are recorded. A graph of \( V \) against \( I \) is then plotted.

The e.m.f. can be written as \( E = I[R + r] \), where \( [R + r] \) is the total resistance in the circuit.

The equation can be written as \( E = IR + Ir \), where \( IR \) is the potential difference across the resistor \( R \) and \( Ir \) is the potential difference across the internal resistance of the cell.

The potential difference across the resistor \( R \) is \( V \).

\[
\therefore E = V + Ir
\]

\[
\therefore V = E - Ir
\]

By comparing the equation above with \( y = mx + c \) for a straight line, it can be seen that plotting a graph of \( V \) against \( I \) gives a straight line where the \( y \)-intercept = e.m.f. of the cell

the gradient = negative the internal resistance of the cell.

**Example**

A cell has an e.m.f. of 1.32 V and internal resistance of \( r \). The cell is connected across the terminals of a resistor of resistance 1.20 \( \Omega \). The cell provides a current of 0.65 A. (See Figure 2.4.5.)

Calculate:

a the total resistance in the circuit

b the internal resistance \( r \)

c the potential difference across the terminals of the cell.

a The e.m.f. of the cell is given by \( E = I[R + r] \)

The total resistance in the circuit = \( R + r = \frac{E}{I} = \frac{1.32}{0.65} = 2.03 \Omega \)

b The total resistance = \( R + r = 2.03 \)

\[ r = 2.03 - R \]

\[ = 2.03 - 1.20 \]

\[ = 0.83 \Omega \]

Therefore the internal resistance \( r = 0.83 \Omega \)

c Potential difference across the terminals of the cell

\[ V = IR = 0.65 \times 1.20 = 0.78 \text{V} \]

**Key points**

- The e.m.f. of a source is defined as the energy converted from chemical (or mechanical) energy into electrical energy per unit charge flowing through it.

- The resistance that is internal to a cell is called the internal resistance.

- The e.m.f. and internal resistance of a cell can be determined experimentally.
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