Volume

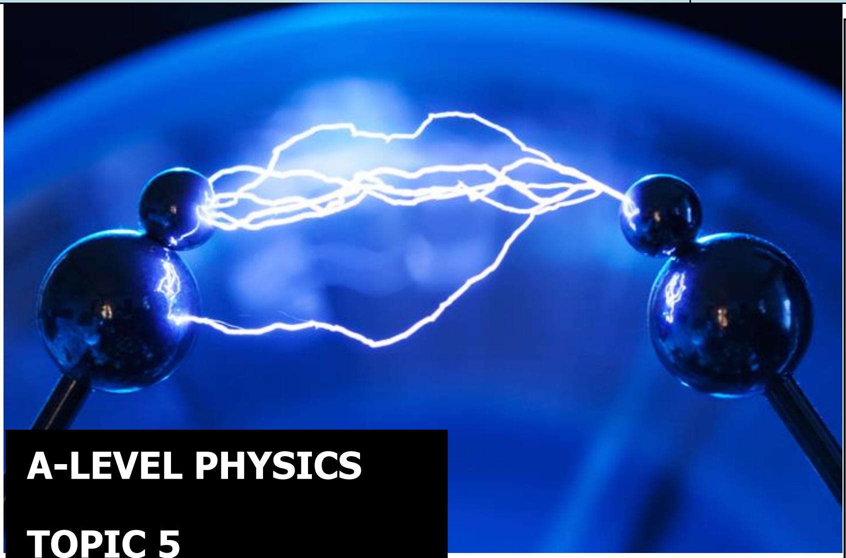
One

ST MARY'S SCIENCE DEPARTMENT:

PHYSICS

A LEVEL PHYSICS **YEAR 1**
STUDENT CLASS BOOK
3.5.1: BASICS OF ELECTRICITY
VOLUME **ONE**

NAME	
PHYSICS CLASS	
MODULE TEACHER	
ALPS GRADE	



A-LEVEL PHYSICS

TOPIC 5

CLASS WORKBOOK 1

THIS MUST BE BROUGHT TO ALL PHYSICS LESSONS.

Contents

3.5.1.1 Basics of Electricity
3.5.1.2 Current-Voltage Characteristics
3.5.1.3 Resistivity
3.5.1.4 Circuits

Overview

This section builds on and develops earlier study of these phenomena from GCSE.

It provides opportunities for the development of practical skills at an early stage in the course and lays the groundwork for later study of the many electrical applications that are important to society.

IMPORTANT NOTE

This book, along with the preparatory reading notes and independent work, must be brought to all Physics lessons with the appropriate teacher.

This book may be used as a learning resource in lessons, you are not fully equipped to learn if this is not used in lesson.

This book may also be used as a revision resource for intervention, internal assessments and external assessments.
Please keep this in your student file.

There are several activities in this book which may not be covered in lessons.

It is advised that students complete these activities outside of lessons as revision aides.

Definition List

Definitions you must learn for this module.

Key Word	Symbol	Definition
Charge carriers		Charged particles that move through a substance when a pd is applied across it such as electrons.
Circuit rule for current (Kirchhoff’s First Law)		**1.** The current passing through two or more components in series is the same through each component. **2.** At a junction, the total current in = the total current out.
Circuit rule for pd (Kirchhoff’s Second Law)		**1.** For two or more components in series, the total pd across all the components is equal to the sum of the pds across each component. **2.** The sum of the EMFs round a complete loop in a circuit = the sum of the pds round the loop.
Current	**I**	The rate of charge carriers moving in an electrical circuit.
Electromotive force (emf),	**ε**	The amount of electrical energy per unit charge produced inside a source of electrical energy.
Ohm’s Law		The pd across a metallic conductor is proportional to the current, provided the physical conditions do not change.
Potential Difference	**PD**	Work done or energy transfer per unit charge between two points when charge moves from one point to another.
Power	**P**	The rate of transfer of energy.
Resistance	**R**	The impedance of charge carriers moving in an electrical circuit. = pd/current.
Resistivity	**ρ**	Resistance per unit length x area of cross-section. The impedance of current based on the properties of the material only.
Semi-conductor		A substance in which the number of charge carriers increases when the temperature is raised.
Thermistor		Resistor which is designed to have a resistance that changes with temperature.

IMPORTANT NOTE
These definitions must be memorised by students.

You will be tested on your knowledge of these definitions.

Equations

The equations below are used in this module.

Quantity/Concept	**Equation(s)**
Current/Charge	$I = \frac{\Delta Q}{\Delta t}$ $\Delta Q = I\,\Delta t$
Potential Difference/EMF	$V = PD = \varepsilon = \frac{\Delta W}{\Delta Q}$
Resistance	$R = \frac{V}{I}$
Electrical Power	$P = VI = I^2R = \frac{V^2}{R}$
Electrical Energy Transferred	$E = Vit = \frac{V^2t}{R} = I^2Rt$
Resistivity	$\rho = \frac{RA}{l}$
Cross Sectional Area of Wire	$A = \prod r^2$ This equation is not given in your examination book.

IMPORTANT NOTE

These equations must be memorised by students.

You will be tested on these equations.

The Language of Measurement

The following subject specific vocabulary provides definitions of key terms used in the A-level Science specifications.

Accuracy
A measurement result is considered accurate if it is judged to be close to the true value.

Calibration
Marking a scale on a measuring instrument.
This involves establishing the relationship between indications of a measuring instrument and standard or reference quantity values, which must be applied.
For example, placing a thermometer in melting ice to see whether it reads 0 °C, to check if it has been calibrated correctly.

Data
Information, either qualitative or quantitative, that has been collected.

Errors
See also uncertainties.

Measurement error
The difference between a measured value and the true value.
anomalies
These are values in a set of results which are judged not to be part of the variation caused by random uncertainty.

Random error
These cause readings to be spread about the true value, due to results varying in an unpredictable way from one measurement to the next.
Random errors are present when any measurement is made, and cannot be corrected. The effect of random errors can be reduced by making more measurements and calculating a new mean.

Systematic error
These cause readings to differ from the true value by a consistent amount each time a measurement is made.
Sources of systematic error can include the environment, methods of observation or instruments used.
Systematic errors cannot be dealt with by simple repeats. If a systematic error is suspected, the data collection should be repeated using a different technique or a different set of equipment, and the results compared.

Zero error
Any indication that a measuring system gives a false reading when the true value of a measured quantity is zero, e.g. the needle on an ammeter failing to return to zero when no current flows.
A zero error may result in a systematic uncertainty.

Evidence
Data which has been shown to be valid.

Fair test
A fair test is one in which only the independent variable has been allowed to affect the dependent variable.

Hypothesis
A proposal intended to explain certain facts or observations.

Interval
The quantity between readings, e.g. a set of 11 readings equally spaced over a distance of 1 metre would give an interval of 10 centimetres.

Precision
Precise measurements are ones in which there is very little spread about the mean value. Precision depends only on the extent of random errors – it gives no indication of how close results are to the true value.

Prediction
A prediction is a statement suggesting what will happen in the future, based on observation, experience or a hypothesis.

Range
The maximum and minimum values of the independent or dependent variables; important in ensuring that any pattern is detected.
For example, a range of distances may be quoted as either:
'From 10 cm to 50 cm'
or
'From 50 cm to 10 cm'

Repeatable
A measurement is repeatable if the original experimenter repeats the investigation using same method and equipment and obtains the same results.

Reproducible
A measurement is reproducible if the investigation is repeated by another person, or by using different equipment or techniques, and the same results are obtained.

Resolution
This is the smallest change in the quantity being measured (input) of a measuring instrument that gives a perceptible change in the reading.

Sketch graph
A line graph, not necessarily on a grid, that shows the general shape of the relationship between two variables. It will not have any points plotted and although the axes should be labelled they may not be scaled.

True value
This is the value that would be obtained in an ideal measurement.

Uncertainty
The interval within which the true value can be expected to lie, with a given level of confidence or probability, e.g. "the temperature is 20 °C ± 2 °C, at a level of confidence of 95%.

Validity
Suitability of the investigative procedure to answer the question being asked. For example, an investigation to find out if the rate of a chemical reaction depended upon the concentration of one of the reactants would not be a valid procedure if the temperature of the reactants was not controlled.

Valid conclusion
A conclusion supported by valid data, obtained from an appropriate experimental design and based on sound reasoning.

Variables
These are physical, chemical or biological quantities or characteristics.

Categoric variables
Categoric variables have values that are labels. E.g. names of plants or types of material.

Continuous variables
Continuous variables can have values (called a quantity) that can be given a magnitude either by counting (as in the case of the number of shrimp) or by measurement (e.g. light intensity, flow rate etc.).

Control variables
A control variable is one which may, in addition to the independent variable, affect the outcome of the investigation and therefore must be kept constant or at least monitored.

Dependent variables
The dependent variable is the variable of which the value is measured for each change in the independent variable.

Independent variables
The independent variable is the variable for which values are changed or selected by the investigator.

IMPORTANT NOTE
These definitions must be memorised by students.

You will be tested on your knowledge of these definitions.

TOPIC: 3.5.1.1 Basics of Electricity

SPEC CHECK

Specification	Completed?
Electric current as the rate of flow of charge; potential difference as work done per unit charge.	
$I = \frac{\Delta Q}{\Delta t}$, $V = \frac{W}{Q}$	
Resistance defined as $R = V/I$	
Students can construct circuits from the range of components.	

NOTES

These notes are brief.

More detailed notes are found in the student preparatory reading book.

Please read the preparatory reading notes.

Definitions

Current, I

Electrical current is the rate of flow of charge in a circuit. Electrons are charged particles that move around the circuit. So, we can think of the electrical current is the rate of the flow of electrons, not so much the speed but the number of electrons moving in the circuit.

If we imagine that electrons are Year 7 students and a wire of a circuit is a corridor, the current is how many students passing in a set time.

Current is measured in Amperes (or Amps), A

Charge, Q

The amount of electrical charge is a fundamental unit, like mass and length and time.
From the data sheet, we can see that the charge on one electron is -1.60×10^{-19} C.
This means that it takes 6.25×10^{18} electrons to transfer 1C of charge.

Charge is measured in Coulombs, C

Voltage/Potential Difference, V

Voltage, or potential difference, is the work done per unit charge.
1 unit of charge is 6.25×10^{18} electrons, so we can think of potential difference as the energy given to each of the electrons, or the pushing force on the electrons. It is the p.d. that causes a current to flow and we can think of it like water flowing in a pipe. If we make one end higher than the other end, water will flow down in, if we increase the height (increase the p.d.) we get more flowing.

If we think of current as Year 7s walking down a corridor, the harder we push them down the corridor the more we get flowing.

Voltage and p.d. are measured in Volts, V

Resistance, R

The resistance of a material tells us how easy or difficult it is to make a current flow through it.
If we think of current as Year 7s walking down a corridor, it would be harder to make the Year 7s flow if we added some Year 11 rugby players into the corridor. Increasing resistance lowers the current.

Resistance is measured in Ohms, Ω

Time, t

You know, time! How long stuff takes and that.

Time is measured in seconds, s

Equations

There are three equations that we need to be able to explain and substitute numbers into.

1

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

This says that the current is the rate of change of charge per second and backs up or idea of current as the rate at which electrons (and charge) flow.

This can be rearranged into

$$\Delta Q = I\Delta t$$

which means that the charge is equal to how much is flowing multiplied by how long it flows for.

2

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

This says that the voltage/p.d. is equal to the energy per charge.
The 'push' of the electrons is equal to the energy given to each charge (electron).

3

$$\boxed{V = IR}$$

This says that increasing the p.d. increases the current.
Increasing the 'push' of the electrons makes more flow.

It also shows us that for constant V, if R increases I gets smaller.
Pushing the same strength, if there is more blocking force less current will flow.

Power

Power is a measure of how quickly something can transfer energy. Power is linked to energy by the equation:

$$\boxed{Power = \frac{Energy}{time}}$$

Power is measured in Watts, W
Energy is measured in Joules, J
Time is measured in seconds, s

New Equations

Energy

$V = \frac{E}{Q}$ can be rearranged into $E = VQ$ and we know that $Q = It$ so combining these equations we get a new one to calculate the energy in an electric circuit:

$E = VQ$ <---------------------- $Q = It$ so $\boxed{E = VIt}$ (1)

Power

If we look at the top equation, to work out power we divide energy by time:

$\frac{E}{t} = \frac{VIt}{t}$ which cancels out to become $\boxed{P = VI}$ (2)

If we substitute $V = IR$ into the last equation, we get another equation for power:

$P = IV$ <---------------------- $V = IR$ so $\boxed{P = I^2R}$ (3)

We can also rearrange $V = IR$ into $I = \frac{V}{R}$ and substitute this into $P = VI$ to get our last equation for power:

$P = VI$ <---------------------- $I = \frac{V}{R}$ so $\boxed{P = \frac{V^2}{R}}$ (4)

Energy again

Two more equations for energy can be derived from the equation at the top and equations 3 and 4

Energy = Power x time

$Pt = I^2Rt$ Equation 3 becomes $\boxed{E = I^2Rt}$ (5)

$Pt = \frac{V^2}{R}t$ Equation 4 becomes $\boxed{E = \frac{V^2}{R}t}$ (6)

REVISION SHEET

Highlight or underline the key information on the revision sheet to consolidate your understanding.

Current is the Rate of Flow of Charge

1) The **current** in a **wire** is like **water** flowing in a **pipe**. The **amount** of water that flows depends on the **flow rate** and the **time**. It's the same with electricity — **current is the rate of flow of charge**.

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

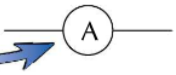
Where I is the current in amperes, ΔQ is the charge in coulombs, and Δt is the time taken in seconds.

Remember that conventional current flows from + to –, the opposite way from electron flow.

2) The **coulomb** is the **unit of charge**.

One coulomb (C) is defined as the **amount of charge** that passes in **1 second** when the **current** is **1 ampere**.

3) You can measure the current flowing through part of a circuit using an **ammeter**. This is the circuit symbol for an ammeter:



Attach an ammeter in series with the component you're investigating.

Potential Difference is the Work Done per Unit Charge

1) To make electric charge flow through a conductor, you need to do **work** on it.
2) **Potential difference** (p.d.), or **voltage**, is defined as the **work done per unit charge moved**:

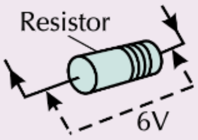
$$V = \frac{W}{Q}$$

W is the work done in joules (see p.34). It's the energy transferred in moving the charge.

The **potential difference** across a component is **1 volt** (V) when you do **1 joule** of work moving **1 coulomb** of charge through the component. This **defines** the volt.

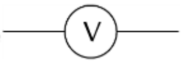
$$1\ \mathrm{V} = 1\ \mathrm{J\,C^{-1}}$$

Back to the 'water analogy' again. The p.d. is like the pressure that's forcing water along the pipe.



Here you do 6 J of work moving each coulomb of charge through the resistor, so the p.d. across it is 6 V. The energy gets converted to heat.

3) You can measure the potential difference across a component using a **voltmeter**. This is the circuit symbol for a voltmeter:



4) Remember, the potential difference across components in parallel is **the same**, so the **voltmeter** should be connected in **parallel** with the component you're investigating.

The maximum value that a voltmeter or ammeter can measure is called the full scale deflection.

Power is the **Rate** of **Transfer** of **Energy**

Power (*P*) is **defined** as the **rate** of **doing work**. It's measured in **watts** (**W**), where **1 watt** is equivalent to **1 joule of work done per second**.

in symbols: $\boxed{P = \frac{W}{t}}$

In an electrical circuit, *W* is the work done moving a charge.

There's a really simple formula for **power** in **electrical circuits**:

$$\boxed{P = VI}$$

This makes sense, since:

1) **Potential difference** (*V*) is defined as the **work done** per **coulomb**.
2) **Current** (*I*) is defined as the **number** of **coulombs** transferred per **second**.
3) So **p.d.** × **current** is **work done per second**, i.e. **power**.

You also know (from the definition of **resistance**) that $V = IR$ (see p.44). **Combining** this with the equation above gives you loads of **different ways** to **calculate power**.

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

Obviously, which equation you should use depends on what **quantities** you're given in the **question**.

Arnold had a pretty high resistance to doing work.

Example: A robotic mutant Santa from the future converts 750 J of electrical energy into heat every second.

a) What is the operating power of the robotic mutant Santa?

b) All of the robotic mutant Santa's components are connected in series, with a total resistance of 30 Ω. What current flows through his wire veins?

a) Power = $W \div t = 750 \div 1 =$ **750 W**

b) $P = I^2R$ so $I = \sqrt{\frac{P}{R}} = \sqrt{\frac{750}{30}} = \sqrt{25} =$ **5.0 A**

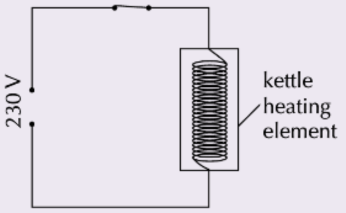
Energy is Easy to **Calculate** if you Know the **Power**

Sometimes it's the **total energy** transferred that you're interested in. In this case you simply need to **multiply** the **power** by the **time**. So: $\boxed{W = VIt}$ (or $W = \frac{V^2}{R}t$ or $W = I^2Rt$)

Make sure that the time is in seconds before you use these equations.

Example: The circuit diagram on the right is part of an electric kettle. A current of 4.0 A flows through the kettle's heating element once it is connected to the mains (230 V).

The kettle takes 4.5 minutes to boil the water it contains. How much energy does the kettle's heating element transfer to the water in the time it takes to boil?



Time the kettle takes to boil in seconds = 4.5 × 60 = 270 seconds.

Use the equation $W = VIt = 230 \times 4.0 \times 270 = 248\,400$ J = **250 kJ (to 2 s.f.)**

Remember, this is the circuit symbol for an open switch:

Reference: CGP Revision Guides

Additional Note Space

Additional Note Space

PUZZLES

To improve your understanding, answer the following puzzles.

The answers are overleaf.

QUESTIONS

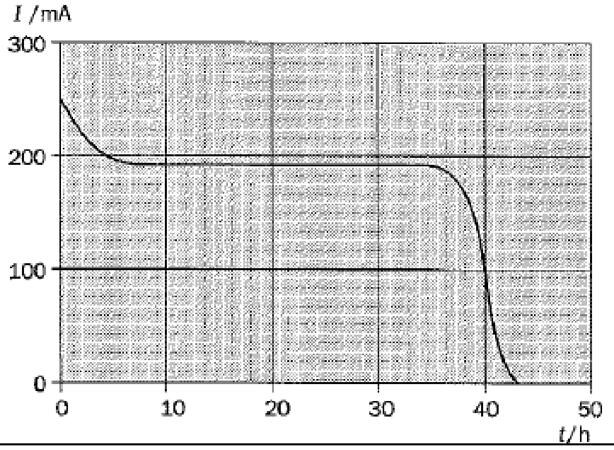
1 What charge flows past any point in an electric circuit if there is a steady current of 6.0 A for 6.0 s?

2 How long will it take for a charge of 350 C to flow past a point in a circuit if the current has a steady value of 0.70 A?

3 A car battery can supply approximately 324 000 C over a period of time of 7.50 h. What steady current does this imply?

4 A watch battery can supply approximately 12 C before it needs to be replaced. Estimate, to the nearest week, how long it will last if the current drawn by the watch is 0.30 µA (1 µA = 10^{-6} A).

5 The supply current from a radio battery (assume continuous running) is shown in the graph. A current of less than 120 mA is ineffective in running the radio. Estimate
(i) the average current supplied before the battery needs replacing
(ii) the charge supplied during the battery's useful life.



Answering Space

ANSWERS

1 36 C

2 500 s

3 12 A

4 66 weeks

5 (i) 190 mA
(ii) 27 000 C

PUZZLES

To improve your understanding, answer the following puzzles.

The answers are overleaf.

QUESTIONS

1 A car battery can supply 6 000 000 J to a car headlamp while delivering 500 000 C of charge through the headlamp. Calculate the potential difference across the headlamp.

2 A car battery supplies a power of 60 W to a car headlamp using a current of 5.0 A. Calculate the potential difference across the headlamp.

3 If questions 1 and 2 apply to the same battery under the same conditions of use, for how long was the battery in use?

4 A 120 W bulb for a projector could be manufactured so that it either operates on 240 V mains or on a 20 V transformer. How much current would be supplied by each supply?

5 A 4600 W electric motor is to operate from a 230 V mains supply. What current will be required? Why might more than this current be needed in practice to obtain this output power?

6 A current of 3.2 mA passes through a circuit component for 300 s. The potential difference across the component is 12 V. How much energy is supplied to the component?

7 During one use of a hairdrier the following quantities are measured. Determine the unknown quantities. Measured quantities: potential difference = 240 V, power = 1200 W, time = 600 s. Unknown quantities: current, charge, energy.

Answering Space

ANSWERS

1 12 V

2 12 V

3 100 000 s

4 0.5 A; 6.0 A

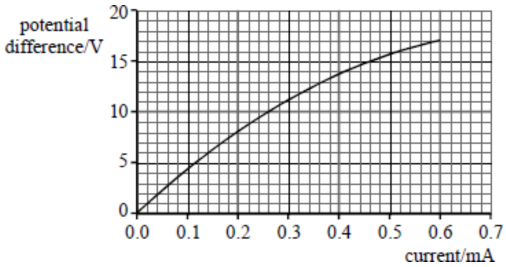
5 20 A. Some power will be lost heating the motor.

6 11.5 J

7 current = 5.0 A; charge = 3000 C; energy = 720 000 J

SAMPLE QUESTION

S1. The diagram below shows a graph of potential difference against current for a thermistor.



S1.1 Sketch an experimental arrangement that you could use to collect the data for this graph.

[3 Marks]

indication of complete circuit with correct components
must show variable resistor / pot divider / variable power supply circuit to be complete
thermistor symbol or resistor labelled 'thermistor'
can omit ammeter / voltmeter here

1 mark

voltmeter correctly placed

1 mark

ammeter correctly placed

1 mark

The thermistor is connected in parallel with a 2.0 kΩ resistor. The current in the resistor is 6.0 mA.

S1.2 Calculate the potential difference across the thermistor.

[2 Marks]

V = (6 / 1000) × 2000

1 mark

= 12 V

1 mark

S1.3 Use the graph to calculate the power dissipated in the thermistor.

[3 Marks]

correct read off

1 mark

power = $I \times V$

1 mark

= $0.34 \times 10^{-3} * 12 = 4.1$ mW

1 mark

S1.4 Describe and explain what happens to the resistance of the thermistor as its temperature increases.

[2 Marks]

decrease in resistance

1 mark

more charge carriers released at high temperature

1 mark

Reference: AQA A-Level Examination Legacy Specimen B

SELF ASSESSMENT

A1. In each of the following circuits the battery has negligible internal resistance and the bulbs are identical.

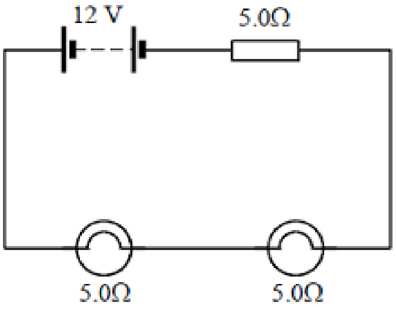


Figure 1

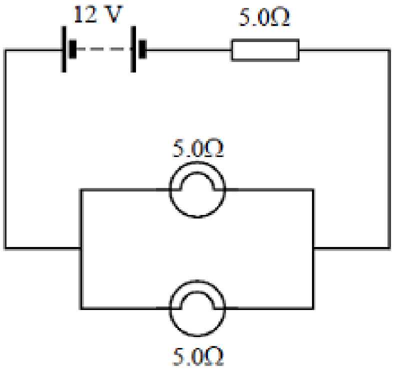


Figure 2

For the circuit shown in **Figure 1** calculate

A1.1 the current flowing through each bulb,

[1 Mark]

……

……

A1.2 the power dissipated in each bulb.

[1 Mark]

……

……

A1.3 In the circuit shown in **Figure 2** calculate the current flowing through each bulb.

[3 Marks]

……

……

……

……

A1.4 Explain how the brightness of the bulbs in **Figure 1** compares with the brightness of the bulbs in **Figure 2**.

[2 Marks]

……

……

Reference: AQA A-Level Examination Legacy Specimen A

Q2. A 2.0 kW heater is used to heat a room from 5 °C to 20 °C. The mass of air in the room is 30 kg. Under these conditions the specific heat capacity of air = 1000 J kg^{-1} K^{-1}.

Calculate

Q2.1 the gain in thermal energy of the air,

[1 Mark]

……

……

Q2.2 the minimum time required to heat the room.

[3 Marks]

……

……

……

……

Q2.3 State and explain **one** reason why the actual time taken to heat the room is longer than the value calculated in part **Q2.2.**

[2 Marks]

……

……

……

……

Reference: AQA A-Level Examination Legacy Specimen A

Q3.1 A steady current of 0.25 A passes through a torch bulb for 6 minutes. Calculate the charge which flows through the bulb in this time.

[2 Marks]

....

....

....

....

The torch bulb is now connected to a battery of negligible internal resistance. The battery supplies a steady current of 0.25 A for 20 hours. In this time the energy transferred in the bulb is 9.0×10^4 J. Calculate

Q3.2 the potential difference across the bulb,

[1 Mark]

....

....

Q3.3 the power of the bulb.

[2 Marks]

....

....

....

....

Reference: AQA A-Level Examination Legacy Specimen A

TOPIC: 3.5.1.2 Current-Voltage Characteristics

SPEC CHECK

Specification	Completed?
For an ohmic conductor, semiconductor diode, and filament lamp.	
Ohm's law as a special case where $I \propto V$ under constant physical conditions.	
Unless specifically stated in questions, ammeters and voltmeters should be treated as ideal (having zero and infinite resistance respectively).	
Questions can be set where either I or V is on the horizontal axis of the characteristic graph.	

NOTES

These notes are brief.

More detailed notes are found in the student preparatory reading book.

Please read the preparatory reading notes.

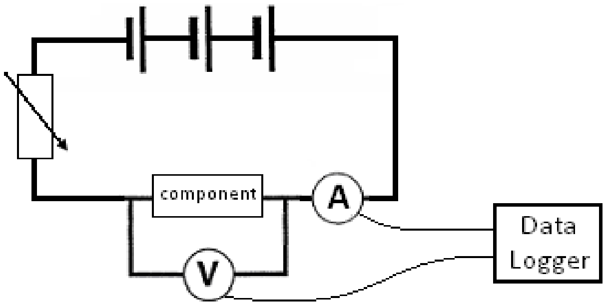
Ohm's Law

We know that a voltage (or potential difference) causes a current to flow and that the size of the current depends on the size of the p.d.

For something to obey Ohm's law the current flowing is proportional to the p.d. pushing it. $V=IR$ so this means the resistance is constant. On a graph of current against p.d. this appears as a straight line.

Taking Measurements

To find how the current through a component varies with the potential difference across it we must take readings. To measure the potential difference, we use a voltmeter connected in parallel and to measure the current we use an ammeter connected in series.



If we connect the component to a battery, we would now have one reading for the p.d. and one for the current. But what we require is a *range* of readings. One way around this would be to use a range of batteries to give different p.d.s. A better way is to add a variable resistor to the circuit, this allows us to use one battery and get a range of readings for current and p.d. To obtain values for current in the negative direction we can reverse either the battery or the component.

I-V Graphs

Resistor

This shows that when p.d. is zero so is the current. When we increase the p.d. in one direction the current increases in that direction. If we apply a p.d. in the reverse direction a current flows in the reverse direction. The straight line shows that current is proportional to p.d. and it obeys Ohm’s law.

Graph **a** has a lower resistance than graph **b** because for the same p.d. less current flows through **b**.

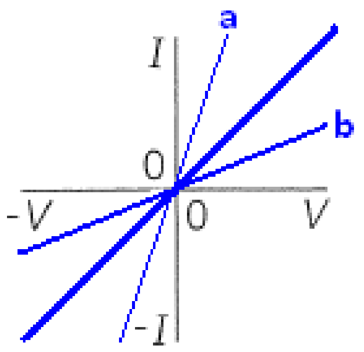
Filament Lamp

At low values the current is proportional to p.d. and so, obeys Ohm’s law.

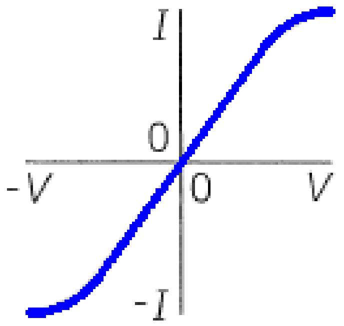
As the potential difference and current increase so does the temperature. This increases the resistance and the graph curves, since resistance changes it no longer obeys Ohm’s law.

Diode

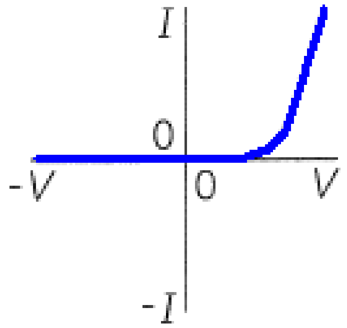
This shows us that in one direction increasing the p.d. increases the current but in the reverse direction the p.d. does not make a current flow. We say that it is forward biased.
Since resistance changes it does not obey Ohm’s law.



Ohmic Resistor



Filament Lamp

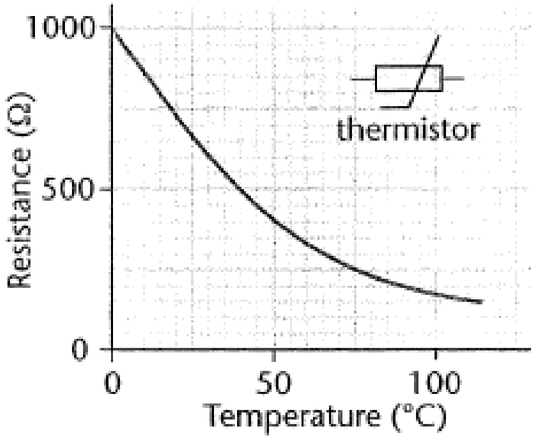


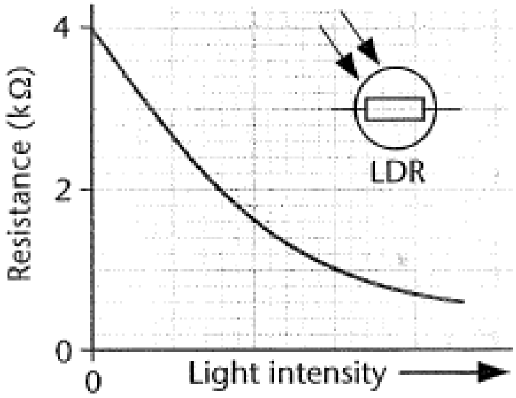
Semiconducting Diode

Three Special Resistors

Variable Resistor

A variable resistor is a resistor whose value can be changed.





Thermistor

The resistance of a thermistor varied with temperature. At low temperatures the resistance is high, at high temperatures the resistance is low.

Light Dependant Resistor (L.D.R)

The resistance of a thermistor varied with light intensity. In dim light the resistance is high and in bright light the resistance is low.

Highlight or underline the key information on the revision sheet to consolidate your understanding.

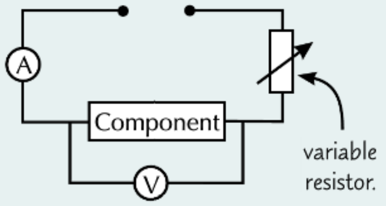
Make sure you learn all the circuit symbols that come up in this section, and know how to design and use circuits using them.

I-V Graphs *Show How* Resistance Varies

The term '***I-V* characteristic**' refers to a **graph** which shows how the **current** (*I*) flowing through a **component changes** as the **potential difference** (*V*) across it is increased.

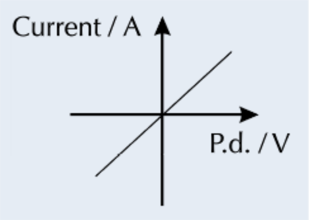
You can investigate the *I-V* characteristic of a component using a **test circuit** like this one:

1) Use the **variable resistor** to alter the **potential difference** across the component and the **current** flowing through it, and record *V* and *I*.
2) **Repeat** your measurements and take **averages** to reduce the effect of random errors on your results.
3) **Plot a graph** of current against potential difference from your results. This graph is the ***I-V* characteristic** of the component.



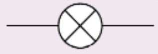
The I-V Characteristic *for a* Metallic Conductor *is a* Straight Line

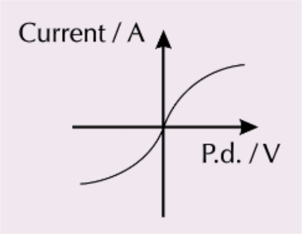
1) At **constant temperature**, the **current** through a **metallic conductor**, e.g. a **wire** or a **resistor**, is **directly proportional** to the **potential difference**.
2) The fact that the characteristic graph is a **straight line through the origin** tells you that the **resistance doesn't change** — it's equal to 1 / gradient.
3) The **shallower** the **gradient** of the characteristic ***I-V*** graph, the **greater** the **resistance** of the conductor.
4) **Metallic conductors** are **ohmic** — they have **constant resistance provided** their temperature doesn't change (see below).



The I-V Characteristic *for a* Filament Lamp *is* Curved

Filament lamp circuit symbol:

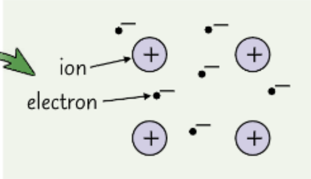




1) The characteristic graph for a **filament lamp** is a **curve**, which starts **steep** but gets **shallower** as the **potential difference rises**.
2) The **filament** in a lamp is just a **coiled up** length of **metal wire**, so you might think it should have the **same characteristic graph** as a **metallic conductor**.
3) However, **current** flowing through the lamp **increases** its **temperature**, so its **resistance increases** (see below).

The Resistivity *of a* Metal *Increases with* Temperature

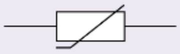
1) **Charge** is carried through **metals** by **free electrons** in a **lattice** of **positive ions**.
2) Heating up a metal makes it **harder** for electrons to **move about**. The **lattice of ions vibrates more** when heated, meaning the electrons **collide** with them more frequently, **transferring** some of their **kinetic energy** into other forms.
3) When kinetic energy is **lost** by the individual electrons, their speed and therefore the **mean drift velocity** (see page 43) decreases. As current is proportional to drift velocity, (***I* = *nqvA***) this means the **current** in the wire **decreases** so its **resistance** (and its resistivity, as it's dimensions haven't changed) **increases**.

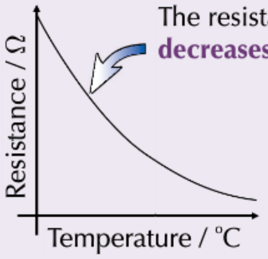


*The **Resistance** of a **Thermistor** Depends on **Temperature***

A **thermistor** is a **resistor** with a **resistance** that depends on its **temperature**. You only need to know about **NTC** thermistors — NTC stands for 'Negative Temperature Coefficient'. This means that the **resistance decreases** as the **temperature goes up**.

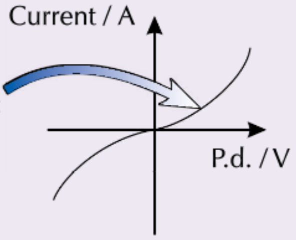
Thermistor circuit symbol:





The resistance of an NTC thermistor **decreases** with **temperature**.

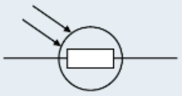
The characteristic ***I-V* graph** for an NTC thermistor looks like this: As the voltage **increases**, the current **increases**. More current leads to an **increase in temperature** and so a **decrease in resistance**. This in turn means more current can flow, so the graph **curves upwards**.



Warming the thermistor gives more **electrons** enough **energy** to **escape** from their atoms. This means that there are **more charge carriers** available, so the **current increases** and the **resistance decreases** (**$R = V/I$**).

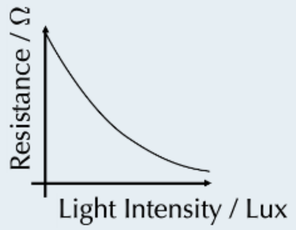
*The **Resistance** of an **LDR** Depends on **Light Intensity***

LDR circuit symbol:

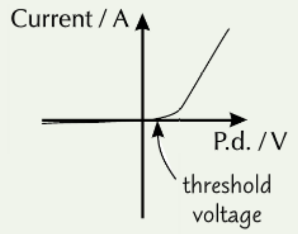


LDR stands for **Light-Dependent Resistor**. The **greater** the intensity of **light** shining on an LDR, the **lower** its **resistance**.

The explanation for this is similar to that for the thermistor. In this case, **light** provides the **energy** that releases more electrons. This means more charge carriers, which means a higher current and a lower resistance.



Diodes** Only Let **Current Flow** in **One Direction



Diodes (including light-emitting diodes (LEDs)) are designed to let **current flow** in **one direction** only. You don't need to be able to explain how they work, just what they do.

1) **Forward bias** is the **direction** in which the **current** is **allowed to flow**.
2) **Most** diodes require a **threshold voltage** of about **0.6 V** in the **forward direction** before they will conduct.
3) In **reverse bias**, the **resistance** of the diode is **very high** and the current that flows is **very tiny**.

Diode circuit symbol:

LED circuit symbol:

Reference: CGP Revision Guides

Additional Note Space

Additional Note Space

SAMPLE QUESTION

S1.1 State Ohm's law.

[2 Marks]

$V \propto I$ [allow proportional]

1 mark

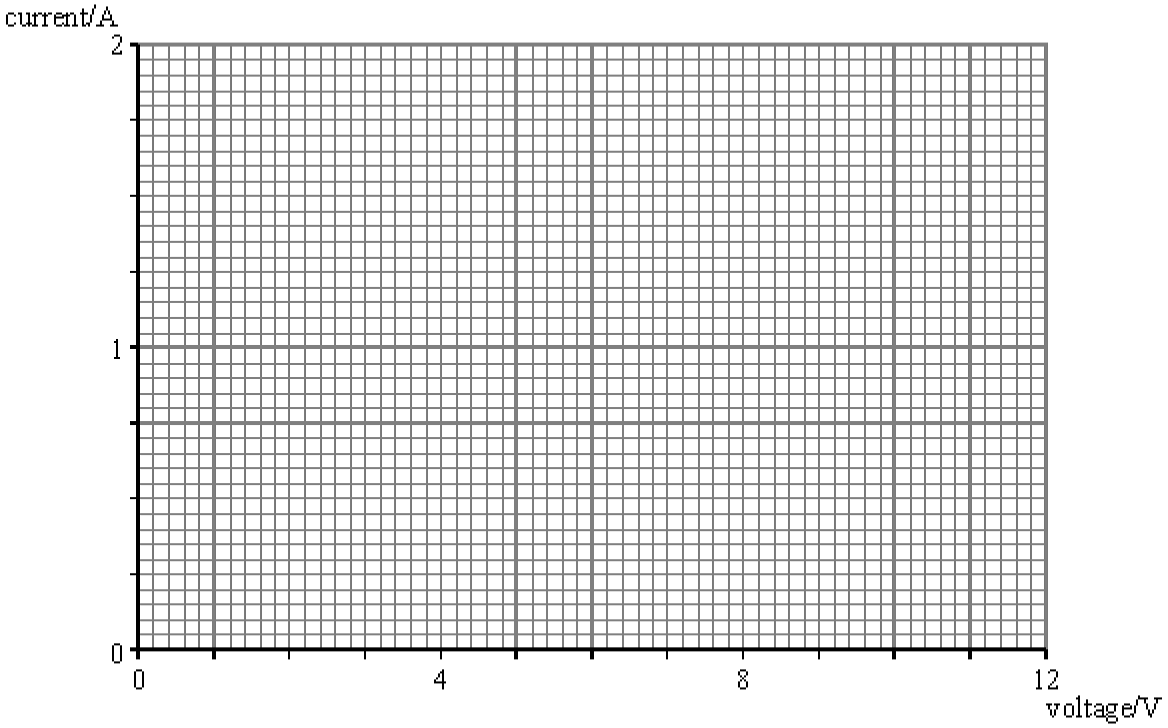
physical condition constant

1 mark

S1.2 A filament lamp labelled '12 V, 2.0 A' has a constant resistance of 2.0 Ω for electrical currents up to 0.50 A.

Sketch on the axes below the current-voltage graph for this lamp over the range of voltages shown. Show clearly any calculations you made in order to answer the question.

[3 Marks]



Line goes through (12, 2) [within one square]

1 mark

Straight line at origin aimed at (1,0.5) and smooth curve (correct shape) beyond (1,0.5)

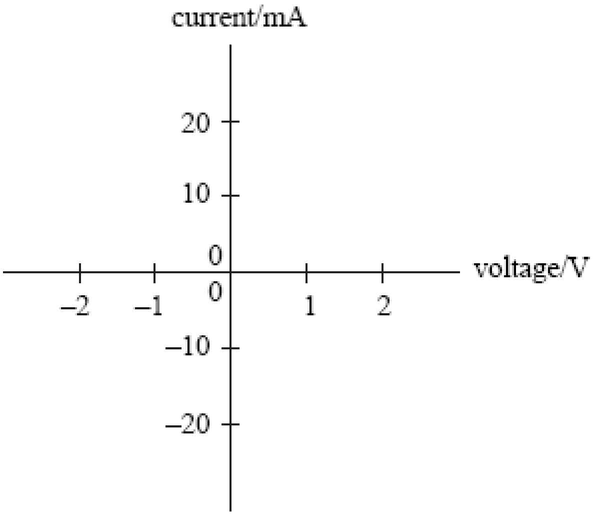
1 mark

Calculation clearly supporting second mark
[$V = IR$, $I = 0.5$, so $V = 1$]

1 mark

S1.3 Sketch on the axes below the current-voltage characteristic for a semi-conductor diode.

[3 Marks]



Correct shape for *V* +ve

1 mark

Non-zero, positive breakaway from *V*-axis,
***V* <= 1V; line not > 1V]**

1 mark

Zero current for reverse bias explicit

1 mark

Reference: AQA A-Level Examination Legacy Specimen B

SELF ASSESSMENT

Q1.1 On the axes in **Figure 1** draw $I-V$ characteristics for **two** components, A and B, both of which obey Ohm's law. Component B has a lower resistance than component A. Label your characteristics clearly as A and B.

[2 Marks]

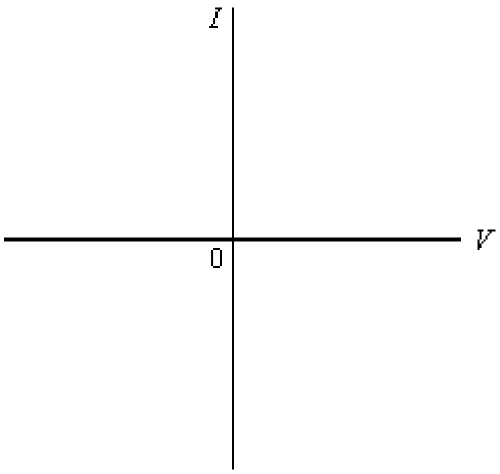


Figure 1

Q1.2 On the axes in **Figure 2** draw the $I-$ V characteristic for a silicon semiconductor diode, giving any relevant voltage values.

[3 Marks]

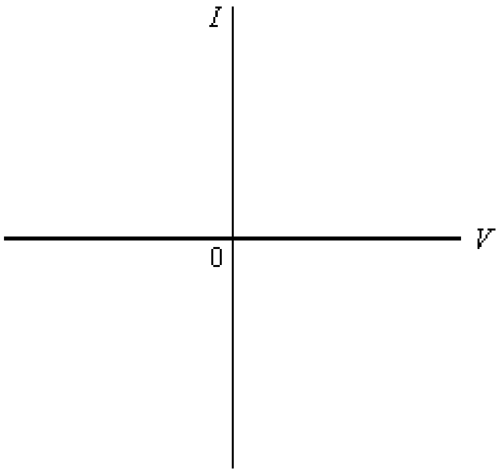


Figure 2

Q1.3 Figure 3 shows the $I - V$ characteristic of a filament lamp. Explain the shape of this characteristic.

[4 Marks]

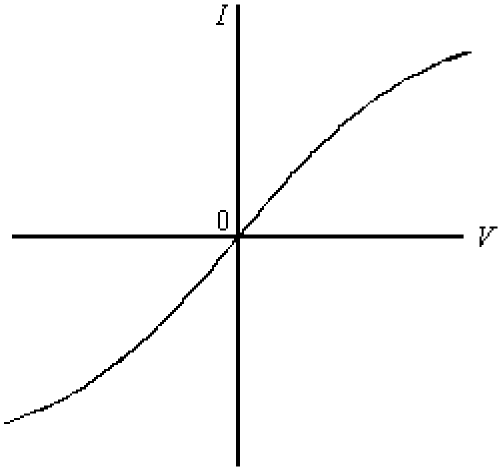


Figure 3

……

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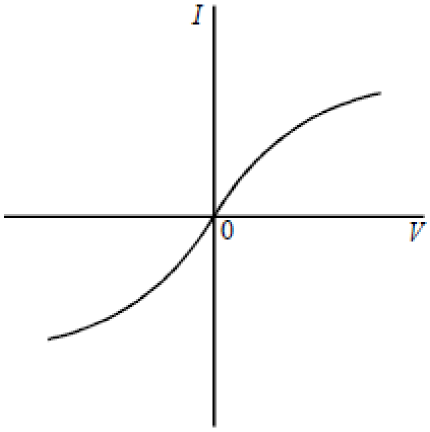
Reference: AQA A-Level Examination Legacy Specimen A

Q2.1 The characteristic shown below is that of a filament lamp.



Explain why, as the voltage is increased either positively or negatively from zero, the characteristic has the form shown in the figure.

[5 Marks]

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Q2.2 At a certain point on the characteristic, the power developed in the lamp is 20 W and the current is 90 mA. Calculate the resistance of the filament at this point on the characteristic.

[2 Marks]

....

....

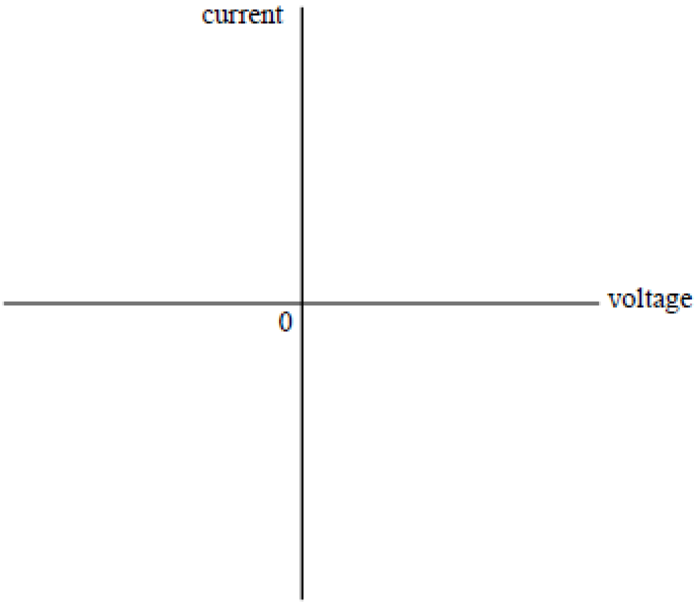
....

....

Reference: AQA A-Level Examination Legacy Specimen A

Q3.1 Draw, on the axes below, the current/voltage characteristic for a filament lamp. Do **not** insert any values for current or voltage.

[3 Marks]



Q3.2 Explain why the characteristic has the shape you have drawn.

[3 Marks]

……

……

……

……

Q3.3 The current/voltage characteristic of a filament lamp is to be determined using a datalogger, the data then being fed into a computer to give a visual display of the characteristic. Draw the circuit diagram required for such an experiment and state what is varied so as to produce a range of values.

[5 Marks]

……

……

……

……

Reference: AQA A-Level Examination Legacy Specimen A

TOPIC: 3.5.1.3 Resistivity

SPEC CHECK

Specification	Completed?
Resistivity, $\rho = \frac{RA}{L}$	
Description of the qualitative effect of temperature on the resistance of metal conductors and thermistors. Only negative temperature coefficient (ntc) thermistors will be considered.	
Applications of thermistors to include temperature sensors and resistance–temperature graphs.	
Superconductivity as a property of certain materials which have zero resistivity at and below a critical temperature which depends on the material.	
Applications of superconductors to include the production of strong magnetic fields and the reduction of energy loss in transmission of electric power.	
Investigation of the variation of resistance of a thermistor with temperature.	

NOTES

These notes are brief.

More detailed notes are found in the student preparatory reading book.

Please read the preparatory reading notes.

Resistance

The resistance of a wire is caused by free electrons colliding with the positive ions that make up the structure of the metal. The resistance depends upon several factors:

Length, l **Length increases – resistance increases**

The longer the piece of wire the more collisions the electrons will have.

Area, A **Area increases – resistance decreases**

The wider the piece of wire the more gaps there are between the ions.

Temperature **Temperature increases – resistance increases**

As temperature increases the ions are given more energy and vibrate more, the electrons are more likely to collide with the ions.

Material

The structure of any two metals is similar but not the same, some metal ions are closer together, others have bigger ions.

Resistivity, ρ

The resistance of a material can be calculate using $\boxed{R = \rho \frac{l}{A}}$

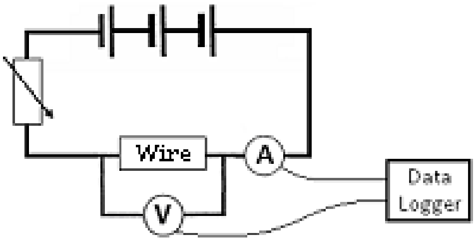
where ρ is the resistivity of the material.

Resistivity is a factor that accounts for the structure of the metal and the temperature. Each metal has its own value of resistivity for each temperature. For example, the resistivity of copper is 1.7×10^{-8} Ωm and carbon is 3×10^{-5} Ωm at room temperature. When both are heated to 100°C their resistivities increase.

Resistivity is measured in Ohm metres , Ωm

Measuring Resistivity

To measure resistivity of a wire we need to measure the length, cross-sectional area (using Area = πr^2) and resistance.



Remember, to measure the resistance we need to measure values of current and potential difference using the set up shown on the right

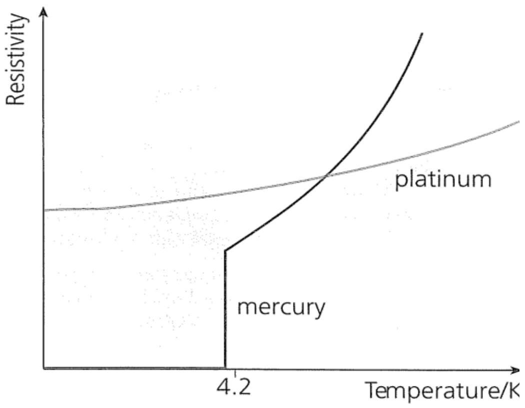
We then rearrange the equation to $\boxed{\rho = \frac{RA}{l}}$ and substitute values in

Superconductivity

The resistivity (and so resistance) of metals increases with the temperature. The reverse is also true that, lowering the temperature lowers the resistivity.

When certain metals are cooled below a *critical temperature* their resistivity drops to zero. The metal now has zero resistance and allows massive currents to flow without losing any energy as heat. These metals are called superconductors. When a superconductor is heated above it's critical temperature it loses its superconductivity and behaves like other metals.

The highest recorded temperature to date is –196°C, large amounts of energy are required to cool the metal to below this temperature.



Uses of Superconductors

High-power electromagnets Power cables Magnetic Resonance Imaging (MRI) scanners

St Mary's Catholic School

REVISION SHEET

Highlight or underline the key information on the revision sheet to consolidate your understanding.

Everything has *Resistance*

1) If you put a **potential difference** (p.d.) across an **electrical component**, a **current** will flow.
2) **How much** current you get for a particular **p.d.** depends on the **resistance** of the component.
3) You can think of a component's **resistance** as a **measure** of how **difficult** it is to get a **current** to **flow** through it.

Mathematically, **resistance** is:
This equation really **defines** what is meant by resistance.

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

This is the **circuit symbol** for a resistor:

4) **Resistance** is measured in **ohms** (Ω).

A component has a resistance of **1 Ω** if a **potential difference** of **1 V** makes a **current** of **1 A** flow through it.

Three Things *Determine Resistance*

If you think about a nice, **simple electrical component**, like a **length of wire**, its **resistance** depends on:

1) **Length** (*l*). The **longer** the wire the **more difficult** it is to make a **current flow**.
2) **Area** (*A*). The **wider** the wire the **easier** it is to make a current flow.
3) **Resistivity** (ρ). This **depends** on the **material** the wire's made from, as the **structure** of the material may make it easy or difficult for charge to flow. In general, resistivity depends on **environmental factors** as well, like **temperature**.

ρ is the Greek letter rho, the symbol for resistivity.

The **resistivity** of a material is defined as the **resistance** of a **1 m length** with a **1 m² cross-sectional area**, so $\rho = \frac{RA}{l}$. Resistivity is measured in **ohm metres** (Ωm).

In your exams, you'll be given this equation in the **form**:

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

where A = cross-sectional area in m², and l = length in m

Typical values for the **resistivity** of **conductors** are **really small**.

However, if you **calculate** a **resistance** for a **conductor** and end up with something **really small** (e.g. 1×10^{-7} Ω), go back and **check** that you've **converted** your **area** into **m²**.

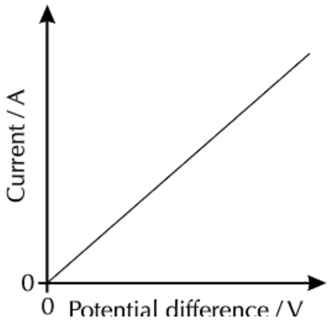
For an Ohmic Conductor, R *is a* Constant

A chap called **Ohm** did most of the early work on resistance. He developed a rule to **predict** how the **current** would **change** as the applied **potential difference increased**, for **certain types** of conductor.

The rule is now called **Ohm's law** and the conductors that **obey** it (mostly metals) d **ohmic conductors**.

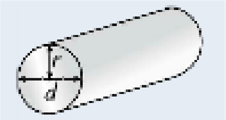
Provided the **temperature** is **constant**, the **current** through an ohmic conductor is **directly proportional** to the **potential difference** across it (that's $I \propto V$).

1) As you can see from the graph, **doubling** the **p.d. doubles** the **current**.
2) What this means is that the **resistance** is **constant**.
3) Often **external factors**, such as **temperature** will have a **significant effect** on resistance, so you need to remember that Ohm's law is **only** true for **ohmic conductors** at **constant temperature**.



To Find the **Resistivity** of a **Wire** You Need to Find its **Resistance**

Before you start, you need to know the **cross-sectional area** of your test wire. Assume that the wire is **cylindrical**, and so the cross-section is **circular**.

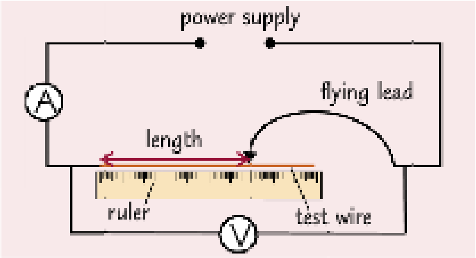


Then you can find its **cross-sectional area** using: **area of a circle = πr^2**

Use a **micrometer** to measure the **diameter** of the test wire for at least **three** different points along the wire. Take an **average** value of the diameter and divide by **2** to get the **radius** (make sure this is in m). Plug it into the equation for cross-sectional area and... **ta da**. Now you can get your teeth into the electricity bit...

A micrometer, sometimes called a micrometer caliper, is used to precisely measure very small distances.

1) The **test wire** should be **clamped** to a ruler and connected to the rest of the circuit at the point where the ruler reads zero.
2) Attach the **flying lead** to the test wire — the lead is just a wire with a crocodile clip at the end to allow connection to any point along the test wire.
3) Record the **length** of the test wire **connected** in the circuit, the **voltmeter reading** and the **ammeter reading**.
4) Use your readings to calculate the **resistance** of the length of wire, using: $R = \frac{V}{I}$
5) Repeat for several **different** lengths within a sensible range, e.g. at 0.10 m intervals from 0.10 m to 1.00 m.
6) Plot your results on a graph of **resistance** against **length**, and draw a **line of best fit** (see page 8).



You could also use a digital multimeter to measure the resistance of the wire directly — you'd connect it in parallel with the length of wire you're investigating and set it to measure resistance.

The **gradient** of the line of best fit is equal to $\frac{R}{l} = \frac{\rho}{A}$. So **multiply** the **gradient** of the line of best fit by the **cross-sectional area** of the wire to find the resistivity of the wire material.

7) The **resistivity** of a material depends on its **temperature**, so you can only find the resistivity of a material **at a certain temperature**. Current flowing in the test wire can cause its temperature to increase, so failing to keep the wire at a **constant temperature** could invalidate your results (see p.12). Try to keep the temperature of the test wire constant by e.g. only having small currents flow through the wire.

Reference: CGP Revision Guides

Additional Note Space

Additional Note Space

PUZZLES

To improve your understanding, answer the following puzzles.

The answers are overleaf.

QUESTIONS

1 Show that the unit of resistivity is the ohm metre (Ω m).

2 The resistivity of copper is 1.7×10^{-8} Ω m. Calculate the resistance of a piece of wire which is 120 m long and which has an area of cross section of 0.65×10^{-6} m^2.

3 A power cable has a diameter of 2.0 cm and is made of aluminium of resistivity 4.3×10^{-8} Ω m. It is used to link a power station to a city 130 km away. Calculate the resistance of the cable.

4 In a transformer 600 turns of copper wire are needed and the average length of each turn is 6.4 cm. Calculate the minimum diameter of the wire that can be used if the total resistance of the wire is not to exceed 2.0 Ω. The resistivity of copper is 1.7×10^{-8} Ω m.

5 Calculate the mass of copper that is needed to give a wire 0.081 mm in diameter a resistance of 200 Ω.
The resistivity of copper is 1.7×10^{-8} Ω m.
The density of copper is 8900 kg m^{-3}.

Answering Space

PUZZLES

To improve your understanding, answer the following puzzles.

The answers are overleaf.

QUESTIONS

1 Three resistors A, B and C each have a potential difference of 6.0 V across them. The current in A is 2.0 A, in B 2.0 mA, and in C 2.0 μA. Calculate the resistances of A, B and C.

2 Calculate the potential difference required across a resistor of resistance 5.7 kΩ if the current through it is 2.5 mA.

3 What current will pass through a resistor of resistance 22 kΩ if the voltage across it is 12.0 V?

4 In an experiment with a light bulb, the following values of V, the applied voltage, and I, the current through the bulb, were obtained.

V/V	**I/A**	**R/Ω**
12.0	2.00	.....
11.0	1.92	.....
10.0	1.82	.....
9.0	1.71	.....
8.0	1.60	.....
7.0	1.48	.....
6.0	1.35	.....
5.0	1.20	.....
4.0	1.00	.....
3.0	0.78	.....
2.0	0.56	.....
1.0	0.28	.....
0.0	0.0	.....

Complete the table to show how the resistance changes with current, and plot two graphs: (i) V against I; (ii) R against I.

Use one piece of paper for the two graphs, and the horizontal scale for current should be the same for both of the graphs.

Answering Space

ANSWERS

1 A = 3.0 Ω; B = 3.0 kΩ; C = 3.0 MΩ

2 14 V

3 0.55 mA

4 All in ohms: 6.00, 5.73, 5.49, 5.26, 5.00, 4.73, 4.44, 4.17, 4.00, 3.85, 3.57, 3.57

5 (a) The graph does not go through the origin but starts, for current zero, at resistance = 1000 Ω. After 3 mA, it falls to a minimum of about 370 at 12.5 mA, before rising to end at about 440 Ω.
(b) Approximately 4.4 V and 5.7 V

6 (a) The graph is a straight line through the origin until V ≈ 4V. It then flattens off until it is nearly horizontal at the end, with a current through it of 2.9 mA.
(b) It could be a resistor, getting hotter as more current passes through it. Resistance increases with temperature.

SAMPLE QUESTION

S1.1 What is a **superconductor**?

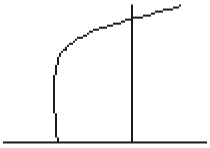
[1 Mark]

(a substance/component/…with) no (electrical) resistance

1 mark

S1.2 With the aid of a sketch graph, explain the term *transition temperature*.

[2 Marks]



graph showing transition temperature

1 mark

temperature below which/at which a material is superconducting

1 mark

S1.3 Explain why superconductors are very useful for applications which require very large electric currents and name **two** such applications.

[3 Marks]

(no resistance) means no energy/heat/power loss

1 mark

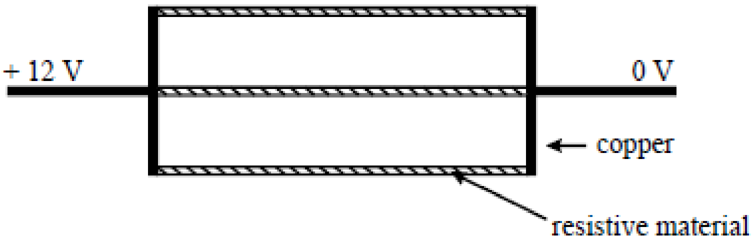
any two from:
power/electrical cables, generators, transformers, motors, electromagnets, MRI scanners, monorail trains, particle accelerators, fusion reactors
not *supercomputers*

2 marks

Reference: AQA A-Level Examination Legacy Specimen B

SELF ASSESSMENT

Q1. A heating element, as used on the rear window of a car, consists of three strips of a resistive material, joined, as shown in the diagram, by strips of copper of negligible resistance. The voltage applied to the unit is 12 V and heat is generated at a rate of 40 W.



Q1.1 Calculate the total resistance of the element.

[2 Marks]

....

....

Q1.2 Hence show that the resistance of a single strip is about 11 Ω.

[3 Marks]

....

....

....

....

Q1.3 If each strip is 2.6 mm wide and 1.1 mm thick, determine the length of each strip.

resistivity of the resistive material = 4.0×10^{-5} Ω m

[3 Marks]

....

....

....

....

Reference: AQA A-Level Examination Legacy Specimen A

Q2. The resistivity of a material in the form of a uniform resistance wire is to be measured. The area of cross-section of the wire is known.

The apparatus available includes a battery, a switch, a variable resistor, an ammeter and a voltmeter.

Q2.1 Draw a circuit diagram using some or all of this apparatus, which would enable you to determine the resistivity of the material.

[3 Marks]

Q2.2 Describe how you would make the necessary measurements, ensuring that you have a range of values.

[4 Marks]

………

………

………

………

………

………

………

………

Q2.3 Show how a value of the resistivity is determined from your measurements.

[2 Marks]

………

………

………

………

………

………

………

………

Q2.4 A sheet of carbon-reinforced plastic measuring 80 mm × 80 mm × 1.5 mm has its two large surfaces coated with highly conducting metal film. When a potential difference of 240 V is applied between the metal films, there is a current of 2.0 mA in the plastic. Calculate the resistivity of the plastic.

[3 Marks]

………

………

………

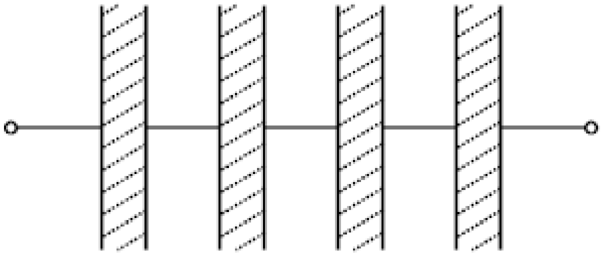
………

………

………

Q2.5 If four of the units described in part (b) are connected as shown in the diagram, calculate the total resistance of the combination.

[2 Marks]



………

………

………

………

Reference: AQA A-Level Examination Legacy Specimen A

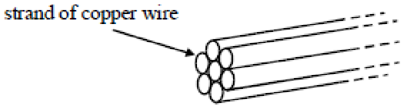
Q3.1 Show that the unit of resistivity is Ω m.

[1 Mark]

....

....

A cable consists of seven straight strands of copper wire each of diameter 1.35 mm as shown in the diagram.



Calculate

Q3.2 the cross-sectional area of **one strand** of copper wire,

[1 Mark]

....

....

Q3.3 the resistance of a 100 m length of the **cable**, given that the resistivity of copper is 1.6×10^{-8} Ωm.

[2 Marks]

....

....

....

....

Q3.4 If the cable in part **Q3.3** carries a current of 20 A, what is the potential difference between the ends of the cable?

[2 Marks]

....

....

....

....

Q3.5 If a single strand of the copper wire in part **Q3.2** carried a current of 20 A, what would be the potential difference between its ends?

[2 Marks]

………

………

Q3.6 State **one** advantage of using a stranded rather than a solid core cable with copper of the same total cross-sectional area.

[1 Mark]

………

………

Reference: AQA A-Level Examination Legacy Specimen A

TOPIC: 3.5.1.4 Circuits

SPEC CHECK

Specification	**Completed?**
Resistors: in series, $R_T = R_1 + R_2 + R_3 + \ldots$ in parallel, $1/R_T = 1/R_1 + 1/R_2 + 1/R_3 + \ldots$	
Energy and power equations: $E = IVt$; $P = IV = I^2R = \frac{V^2}{R}$	
The relationships between currents, voltages and resistances in series and parallel circuits, including cells in series and identical cells in parallel.	
Conservation of charge and conservation of energy in dc circuits.	
Students can construct circuits with various component configurations and measure currents and potential differences.	

NOTES

These notes are brief.

More detailed notes are found in the student preparatory reading book.

Please read the preparatory reading notes.

Series Circuits

In a series circuit, all the components are in one circuit or loop. If resistor 1 in the diagram was removed this would break the whole circuit.

The total current of the circuit is the same at each point in the circuit.

$$\boxed{I_{TOTAL} = I_1 = I_2 = I_3}$$

The total voltage of the circuit is equal to the sum of the p.d.s across each resistor.

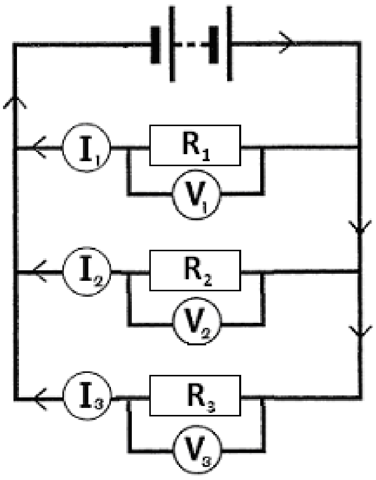
$$\boxed{V_{TOTAL} = V_1 + V_2 + V_3}$$

The total resistance of the circuit is equal to the sum of the resistance of each resistor.

$$\boxed{R_{TOTAL} = R_1 + R_2 + R_3}$$

Parallel Circuits

Components in parallel have their own separate circuit or loop. If resistor 1 in the diagram was removed this would only break that circuit, a current would still flow through resistors 2 and 3.



The total current is equal to the sum of the currents through each resistor.

$$\boxed{I_{TOTAL} = I_1 + I_2 + I_3}$$

The total potential difference is equal to the p.d.s across each resistor.

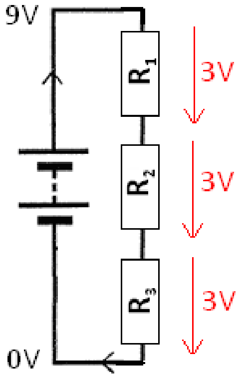
$$\boxed{V_{TOTAL} = V_1 = V_2 = V_3}$$

The total resistance can be calculated using the equation:

$$\boxed{\frac{1}{R_{TOTAL}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

Water Slide Analogy

Imagine instead of getting a potential difference we get a height difference by reaching the top of a slide. This series circuit has three connected slides and the parallel circuit below has three separate slides that reach the bottom.



Voltages/P.D.s

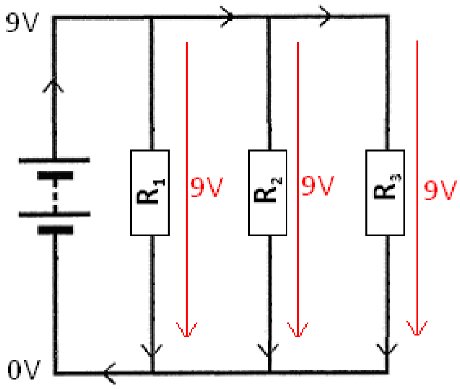
In series, we can see that the total height loss is equal to how much you fall on slide 1, slide 2 and slide 3 added together. This means that the total p.d. lost must be the p.d. given by the battery. If the resistors have equal values this drop in potential difference will be equal.

In parallel we see each slide will drop by the same height meaning the potential difference is equal to the total potential difference of the battery.

Currents

If we imagine 100 people on the water slide, in series we can see that 100 people get to the top. All 100 must go down slide 1 then slide 2 and final slide 3, there is no other option.
So, the current in a series circuit is the same everywhere.

In parallel we see there is a choice in the slide we take. 100 people get to the top of the slide but some may go down slide 1, some down slide 2 and some down slide 3. The total number of people is equal to the number of people going down each slide added together, and the total current is equal to the currents in each circuit/loop.



REVISION SHEET

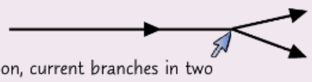
Highlight or underline the key information on the revision sheet to consolidate your understanding.

Charge Doesn't 'Leak Away' Anywhere — it's Conserved

1) As **charge flows** through a circuit, it **doesn't** get **used up** or **lost**.
2) This means that whatever charge flows **into** a junction will flow **out** again.
3) Since **current** is **rate of flow of charge**, it follows that whatever current flows **into** a junction is the same as the current flowing **out** of it.

Example: 6 coulombs of charge flow into a junction in 1 second, and split in the ratio 1:2.

$Q_1 = 6\text{ C} \Rightarrow I_1 = 6\text{ A}$



$Q_2 = 2\text{ C} \Rightarrow I_2 = 2\text{ A}$

$Q_3 = 4\text{ C} \Rightarrow I_3 = 4\text{ A}$

$I_1 = I_2 + I_3$

Kirchhoff's first law says:

The total **current entering a junction** = the total **current leaving it.**

You'll probably see these laws called "conservation laws" rather than "Kirchhoff's laws" in the exam.

Energy is Conserved too

1) **Energy is conserved**. You already know that. In **electrical circuits**, **energy** is **transferred round** the circuit. Energy **transferred to** a unit charge is **e.m.f.**, and energy **transferred from** a unit charge is **potential difference**.
2) In a **closed loop**, these two quantities must be **equal** if energy is conserved (which it is).

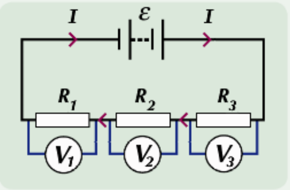
Kirchhoff's second law says:

The **total e.m.f.** around a **series circuit** = the **sum** of the **p.d.**s across each component. (or $\varepsilon = \Sigma IR$ in symbols)

The Conservation Laws Apply to Different Combinations of Resistors

A **typical exam question** will give you a **circuit** with bits of information missing, leaving you to fill in the gaps. Not the most fun... but on the plus side you get to ignore any internal resistance stuff (unless the question tells you otherwise)... hurrah. You need to remember the **following rules**:

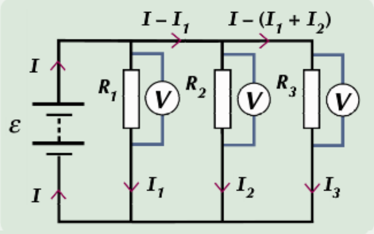
Series Circuits:



1) **same current** at **all points** of the circuit (since there are no junctions)
2) **e.m.f. split** between **components** (by Kirchhoff's 2nd law), so: $\varepsilon = V_1 + V_2 + V_3$
3) $V = IR$, so if I is constant: $IR_{total} = IR_1 + IR_2 + IR_3$
4) cancelling the Is gives:

$$\boxed{R_{total} = R_1 + R_2 + R_3}$$

Parallel Circuits:



1) **current** is **split** at each **junction**, so: $I = I_1 + I_2 + I_3$
2) **same p.d.** across **all components** (remember that within a loop the e.m.f. equals the sum of individual p.d.s)
3) so, $V/R_{total} = V/R_1 + V/R_2 + V/R_3$
4) cancelling the Vs gives:

$$\boxed{\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

Reference: CGP Revision Guide

Additional Note Space

Additional Note Space

PUZZLES

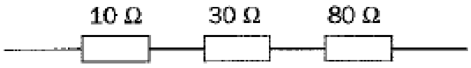
To improve your understanding, answer the following puzzles.

The answers are overleaf.

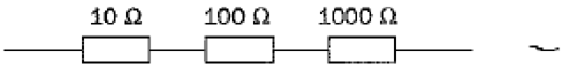
QUESTIONS

1 Find the total resistance in each of the following combinations of resistors.

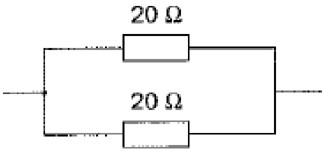
(a)



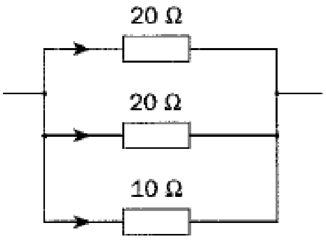
(b)



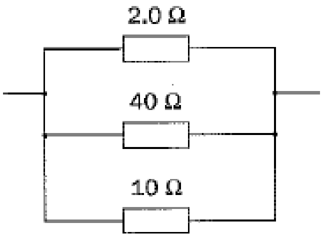
(c)



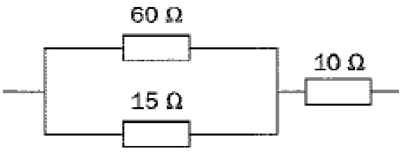
(d)



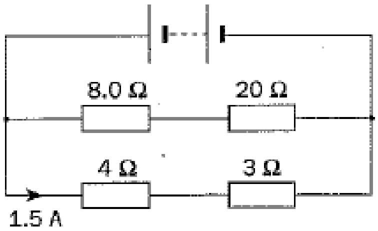
(e)



(f)



2



Given the information on this circuit diagram find
(a) the e.m.f. of the battery
(b) the current in the 20 Ω resistor
(c) the power supplied to each of the four resistors.

Answering Space

ANSWERS

1 (a) 120 Ω
(b) 1110 Ω
(c) 10 Ω
(d) 5 Ω
(e) 1.6 Ω
(f) 22 Ω

2 (a) 10.5 V
(b) 0.38 A
(c) 1.13 W; 2.8 W; 9.0 W; 6.75 W

3 (a) 2.0 Ω
(b) 3.0 A
(c) 3.0 V
(d) 3.0 V across each of them
(e) 1.5 W
(f) 50%

4 Note that the equation is best written as

$$\frac{1}{0.95R} = \frac{1}{R} + \frac{1}{xR}$$

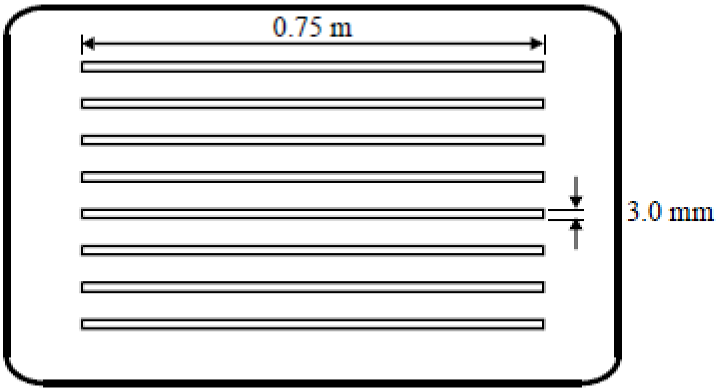
so R cancels and gives x as 19, with the parallel resistance $19R$.

5 2.4 V, 2.0 Ω

6 $E = 7.86$ V, $r = 1.24$ Ω

SAMPLE QUESTION

S1. A manufacturer asks you to design the heating element in a car rear-window de-mister. The design brief calls for an output of 48 W at a potential difference of 12 V. The diagram below shows where the eight elements will be on the car window before electrical connections are made to them.



S1.1 Calculate the current supplied by the power supply.

[1 Mark]

$I = P / V$ = 48 / 12 = 4.0 A

1 mark

One design possibility is for the eight elements to be connected in parallel.

S1.2 Calculate the current in each element in this parallel arrangement.

[1 Mark]

I = 0.5 A **1 mark**

S1.3 Calculate the resistance required for each element.

[2 Marks]

$R = V / I$ = 12 / 0.5

1 mark

= 24 ohm

1 mark

Another design possibility is to have the eight elements connected in series.

S1.4 Calculate the current in each element in this series arrangement.

[1 Mark]

I = 4A **1 mark**

S1.5 Calculate the resistance required for each element.

[2 Marks]

R = 1.50 / 4

1 mark

= 0.37(5) ohm

1 mark

S1.6 State **one** disadvantage of the series design compared to the parallel arrangement.

[1 Mark]

failure of one element breaks whole unit

1 mark

The series design is adopted. Each element is to have a rectangular cross-section of 0.12 mm by 3.0 mm. The length of each element is to be 0.75 m.

S1.7 State the units of resistivity.

Ohm Metre
1 mark **(1)**

S1.8 Calculate the resistivity of the material from which the element must be made.

[2 Marks]

$p = RA / I$ **[**$= 0.375 \times (3.0 \times 10^{-3}) \times (0.12 \times 10^{-3}) / 0.75$**]**

1 mark

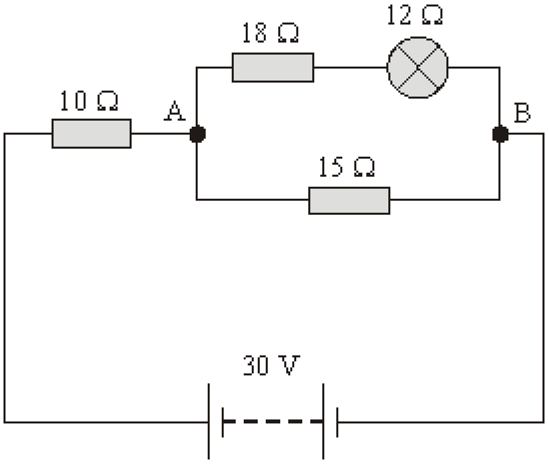
$= 1.8 \times 10^{-7}$ **[** Ω **m]**

1 mark

Reference: AQA A-Level Examination Legacy Specimen B

SELF ASSESSMENT

A1. In the circuit shown in the figure below, the battery, of negligible internal resistance, has an emf of 30 V. The pd across the lamp is 6.0 V and its resistance is 12 Ω.



A1.1 Show that the total resistance of the circuit is 20 Ω.

[3 Marks]

………

………

………

………

Calculate

A1.2 the current supplied by the battery,

[1 Mark]

………

………

A1.3 the pd between the points A and B,

[1 Mark]

………

………

A1.4 the current in the lamp.

[2 Marks]

………

………

A1.5 What is the power of the lamp, in W?

[1 Mark]

....

....

A1.6 What percentage of the power supplied by the battery is dissipated in the lamp?

[2 Marks]

....

....

Reference: AQA A-Level Examination Legacy Specimen A

Q2. A set of decorative lights consists of a string of lamps. Each lamp is rated at 5.0 V, 0.40 W and is connected in series to a 230 V supply.

Calculate

A2.1 the number of lamps in the set, so that each lamp operates at the correct rating,

[1 Mark]

....

....

A2.2 the current in the circuit,

[1 Mark]

....

....

A2.3 the resistance of each lamp,

[1 Mark]

....

....

A2.4 the total electrical energy transferred by the set of lights in 2 hours.

[2 Marks]

....

....

....

When assembled at the factory, one set of lights inadvertently contains 10 lamps too many. All of them are connected in series. Assume that the resistance of each lamp is the same as that calculated in part A2.3.

A2.5 Calculate the current in this set of lights when connected to a 230 V supply.

....

....

A2.6 How would the brightness of each lamp in this set compare with the brightness of each lamp in the correct set?

[3 Marks]

....

....

....

....

Reference: AQA A-Level Examination Legacy Specimen A

Q3.1 Figure 1 shows two possible arrangements of connecting three resistors, each resistor having a resistance of 40 Ω.

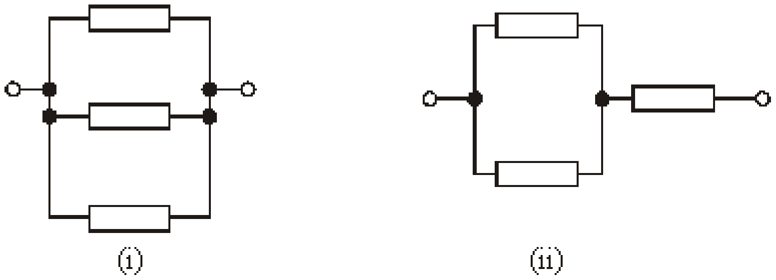


Figure 1

Calculate the equivalent resistance in each case.

[3 Marks]

(i)

....

....

(ii)

....

....

....

The designer of a heating element for the rear window of a car decides to connect six separate heating elements together as shown in **Figure 2**. Each element has a resistance of 6.0 Ω and the unit is connected to a 12 V dc supply having zero internal resistance.

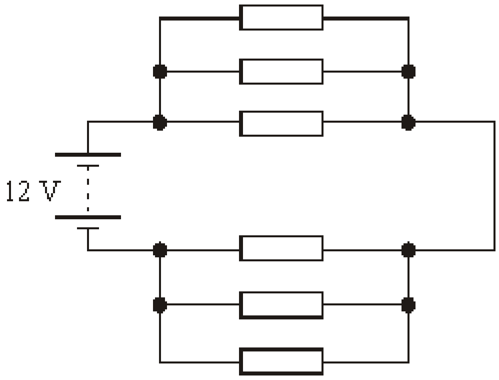


Figure 2

Q3.2 Calculate the current in each single element.

[2 Marks]

....

....

....

....

....

....

Q3.3 With the aid of a similar calculation give a reason why the heater would not be as effective if all six were connected in series.

[3 Marks]

....

....

....

....

Reference: AQA A-Level Examination Legacy Specimen A

STRETCH AND CHALLENGE
UPGRADE YOUR PHYSICS

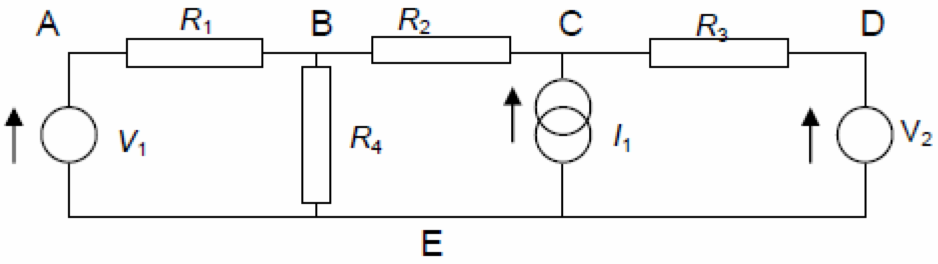
The following section include information beyond the A-Level Physics.
This information will further your understanding and provide a bridge to University Level Physics.

6.3 *Circuits – putting it together*

In this section, we look at combining resistors, capacitors and inductors in electrical circuits. There are two reasons for doing this. Firstly, once you have left school, you will be faced with complicated electronic networks, and you need to be able to analyse these just as well as the simple series and parallel arrangements you dealt with in the classroom. Secondly, engineers frequently use electric circuits as models or analogies for other systems (say, an oscillating bridge or the control of the nervous system over the muscles in a leg) – the better you understand electric circuits, the better you will understand any linked system.

6.3.1 Circuit Analysis

Our aim here is to be able to solve a circuit like the one below. The circles represent constant-voltage sources (a bit like cells or batteries) and the linked circles represent constant-current sources. Our aim is to find voltage difference across each component, and also to work out the current in each resistor.



In order to solve the circuit, we use two rules – the Kirchoff Laws. Kirchoff's 1st says that the total current going into a junction is equal to the total current leaving it. Therefore, at B in the circuit below, we would say that $I_{BE} = I_{AB} + I_{CB}$, where I_{BE} means the current flowing from B to E (through R_4).

Kirchoff's 2nd Law is that voltages always add up correctly. In other words, no matter which route we took from E to B, say, we would agree on the voltage difference between E and B. In symbols, if V_{BE} means the difference in potential (as measured by a voltmeter) between B and E, then we have $V_{BE} = V_{AE} + V_{BA}$. This is basically the same thing as the law of conservation of energy. The voltage (or, more strictly, the *potential*) at B, V_B, is the energy content of one coulomb of charge at B. In travelling to E, it will lose V_B-V_E joules, irrespective of the route taken.[23] In fact, we assume the truth of Kirchoff's 2nd Law whenever we say, "let's call the voltage at A 'V_A'," for we are assuming that the voltage of A does not depend on the route used to measure it.

Using these two rules, and the equation for the current through a resistor (for example, $V_{BA} = I_{BA} R_1$), we may write down a set of equations for the circuit. Notice that because currents are said to go from + to –, this means that if V_{AB} (the voltage of A, measured relative to B) is positive, then V_A is bigger than V_B, and hence I_{AB} will be positive too. To make the notation easier we will take the potential at E to be zero. In symbolic form, this means that we shall call V_{BE} (that is, $V_B – V_E$) V_B for short.

Kirchoff's First Law:

$$I_{EA} = I_{AB}; \quad I_{BE} = I_{AB}+I_{CB}; \quad I_1 = I_{CB}+I_{CD}; \quad I_{CD} = I_{DE}$$

Kirchoff's Second Law:

$$\begin{aligned} V_B &= I_{BE} R_4 \\ &= V_A + V_{BA} = V_1 - I_{AB} R_1 \\ &= V_D + V_{CD} + V_{BC} = V_2 + I_{CD} R_3 - I_{CB} R_2 \end{aligned}$$

After elimination, the equations reduce to two:

$$V_1 - I_{AB} R_1 = V_2 + I_1 R_3 - (R_3 + R_2) I_{CB} = (I_{AB} + I_{CB}) R_4,$$

and from these the currents I_{AB} and I_{CB} can be found (after a bit of messy algebra). After this, the remaining currents and voltages are straightforward to determine.

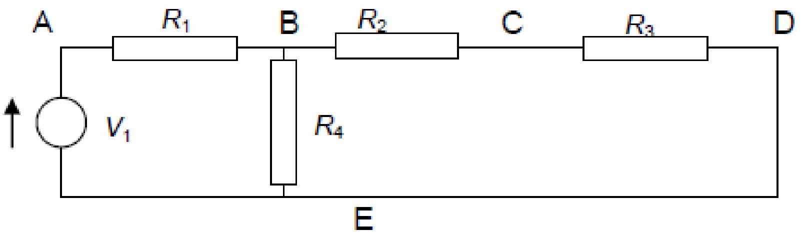
These principles can be used to solve any circuit. However, as networks get bigger, it is useful to find more prescriptive methods of solution, which could be used by a computer. We shall cover two methods here – for certain problems, they may be more efficient than the direct application of Kirchoff's Laws.

6.3.1.1 *Method of Superposition*

The method of superposition relies on the fact that for a simple resistor, the current is proportional to the voltage. It follows that if current I_1 causes a voltage difference of 3V, and current I_2 causes a voltage difference of 5V, then current I_1+I_2 will cause an 8V p.d. across the component. Here is the procedure:

- Choose one of the supply components.
- Remove the other supply components from the circuit. Replace voltage sources with direct connections (short circuits), and leave breaks in the circuit where the current sources were (open circuits).
- Calculate the current in each wire, and the voltage across each component.
- Repeat the procedure for each supply component in turn.
- The current in each wire for the original (whole) circuit is equal to the sum of the currents in that wire due to each supply unit.
- The voltage across each component in the original (whole) circuit is equal to the sum of the voltages across that component due to each supply unit.

Let's use this method to analyse the circuit above. We start by considering only source V_1. Removing the other supply components gives us a circuit like this.



This circuit is easier to analyse as it only has one supply. Supply V_1 feeds a circuit with resistance

$$R_1 + \{R_4 // (R_2+R_3)\}$$

$$= R_1 + \frac{R_4\left(R_2 + R_3\right)}{R_4 + R_2 + R_3}$$

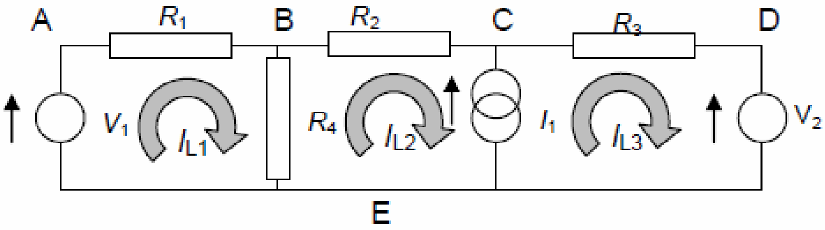
where // means 'in parallel with.' Accordingly, the current supplied by V_1 (and the current through R_1 which is in series with it) is equal to V_1 divided by this resistance. The voltages of points B, C and D can be calculated, as can the current in each wire. We make a note of the values, and add to them the results of analyses of circuits only containing I_1 and only containing V_2.

You may find this method good in the sense that you only have to deal with one supply component at a time – and therefore all you need to know is how to combine resistors (something you've done before). Having said that, we end up analysing three circuits rather than one, so it is more time consuming.

Before leaving the method, you may be curious why voltage sources were replaced with short circuits, and current sources with open circuits. Here's the reason. A voltage source does not change the voltage across its terminals, no matter what the current is (d Voltage / d Current = $R_{equivalent}$ = 0). The only type of resistor which behaves likewise is a perfect conductor (0Ω). Similarly, a current source does not change its current, no matter what the voltage (d Current / d Voltage = 1 / $R_{equivalent}$ = 0). The equivalent resistor in this case is a perfect insulator (∞Ω) which lets no current through ever.

6.3.1.2 *Method of Loop Currents*

Here we break the circuit down into the smallest loops it contains. Here there are three loops:



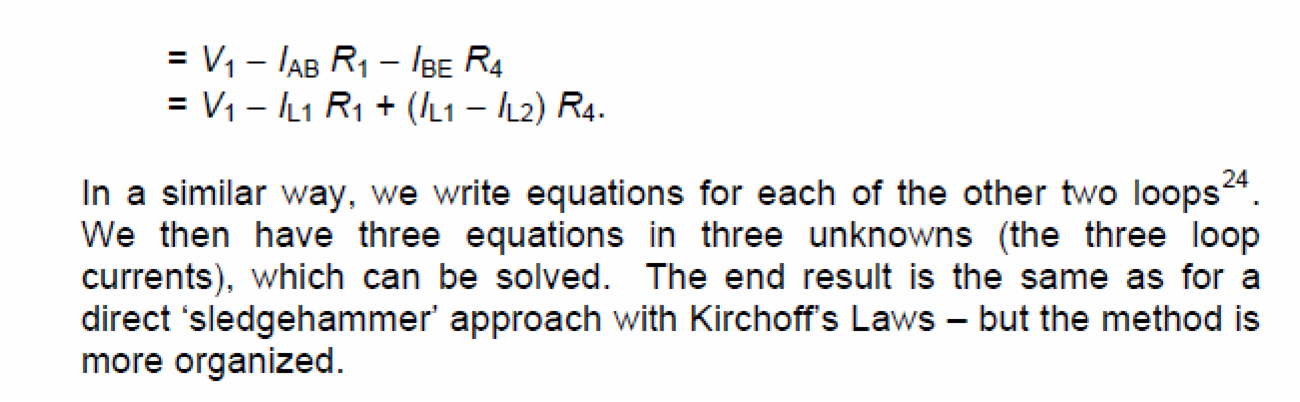
- E to A to B and back to E (loop 1),
- E to B to C to E (loop 2), and
- E to C to D to E (loop 3).

We call the current in loop 1 "loop current" number one (I_{L1}), with I_{L2} and I_{L3} representing the currents in the other two loops. We then express all other currents in terms of the loop currents. Clearly, $I_{AB} = I_{L1}$, since R_1 is in the first loop alone. Similarly, $I_{BC} = I_{L2}$, and $I_{CD} = I_{L3}$.

The current through R_4 is more complex, since this resistor is part of two of the loops. We write $I_{BE} = I_{L1} - I_{L2}$. Here I_{L1} is positive, since I_{BE} is in the same direction as I_{L1}, whereas I_{L2} (which goes from E to B then on to C) is in the opposite direction. These designations automatically take care of Kirchoff's First Law. Notice that by this method, $I_1 = I_{L3} - I_{L2}$.

Each loop now contributes one equation – Kirchoff's 2nd law around that loop. Clearly, if you go all the way round the loop, you must return to the voltage you started with. Taking the first loop as an example, we have:

$$0 = V_{AE} + V_{BA} + V_{EB}$$



$= V_1 - I_{AB} R_1 - I_{BE} R_4$

$= V_1 - I_{L1} R_1 + (I_{L1} - I_{L2}) R_4.$

In a similar way, we write equations for each of the other two loops[24]. We then have three equations in three unknowns (the three loop currents), which can be solved. The end result is the same as for a direct ‘sledgehammer’ approach with Kirchoff’s Laws – but the method is more organized.

REVISION CHECKLIST

Specification reference	Checklist questions	
3.5.1.1	Can you explain electric current as the rate of flow of charge?	☐
3.5.1.1	Can you explain potential difference as work done per unit charge?	☐
3.5.1.1	Can you use the formulae $I = \frac{\Delta Q}{\Delta t}$ and $V = \frac{W}{Q}$?	☐
3.5.1.1	Can you define resistance as $R = \frac{V}{I}$?	☐
3.5.1.2	Can you recognise and use ohmic conductors, semiconductor diodes, and filament lamps?	☐
3.5.1.2	Can you explain Ohm’s law as a special case where $I \propto V$ under constant physical conditions?	☐
3.5.1.2	Can you interpret characteristic graphs where I or V is on the horizontal axis?	☐
3.5.1.3	Can you explain resistivity and use the equation $\rho = \frac{RA}{L}$?	☐
3.5.1.3	Can you describe the effect of temperature on the resistance of metal conductors and thermistors?	☐
3.5.1.3	Can you describe application of thermistors as temperature sensors?	☐
3.5.1.3	Can you describe and sketch how resistance varies with temperature for a metal wire and for a thermistor?	☐
3.5.1.3	Can you describe superconductivity as a property of certain materials that have zero resistivity at/below a critical temperature which depends on the material?	☐
3.5.1.3	Can you describe some applications of superconductors, including their use in the production of strong magnetic fields and the reduction of energy loss in transmission of electric power?	☐
3.5.1.3	Have you carried out a practical to determine resistivity of a wire using a micrometer, ammeter, and voltmeter?	☐

DATASHEET

DATA – FUNDAMENTAL CONSTANTS AND VALUES

Quantity	Symbol	Value	Units
speed of light in vacuo	c	3.00×10^{8}	$\mathrm{m\ s^{-1}}$
permeability of free space	μ_0	$4\pi \times 10^{-7}$	$\mathrm{H\ m^{-1}}$
permittivity of free space	ε_0	8.85×10^{-12}	$\mathrm{F\ m^{-1}}$
magnitude of the charge of electron	e	1.60×10^{-19}	C
the Planck constant	h	6.63×10^{-34}	$\mathrm{J\ s}$
gravitational constant	G	6.67×10^{-11}	$\mathrm{N\ m^{2}\ kg^{-2}}$
the Avogadro constant	N_{A}	6.02×10^{23}	$\mathrm{mol^{-1}}$
molar gas constant	R	8.31	$\mathrm{J\ K^{-1}\ mol^{-1}}$
the Boltzmann constant	k	1.38×10^{-23}	$\mathrm{J\ K^{-1}}$
the Stefan constant	σ	5.67×10^{-8}	$\mathrm{W\ m^{-2}\ K^{-4}}$
the Wien constant	α	2.90×10^{-3}	$\mathrm{m\ K}$
electron rest mass (equivalent to 5.5×10^{-4} u)	m_{e}	9.11×10^{-31}	kg
electron charge/mass ratio	$\frac{e}{m_{\mathrm{e}}}$	1.76×10^{11}	$\mathrm{C\ kg^{-1}}$
proton rest mass (equivalent to 1.00728 u)	m_{p}	$1.67(3) \times 10^{-27}$	kg
proton charge/mass ratio	$\frac{e}{m_{\mathrm{p}}}$	9.58×10^{7}	$\mathrm{C\ kg^{-1}}$
neutron rest mass (equivalent to 1.00867 u)	m_{n}	$1.67(5) \times 10^{-27}$	kg
gravitational field strength	g	9.81	$\mathrm{N\ kg^{-1}}$
acceleration due to gravity	g	9.81	$\mathrm{m\ s^{-2}}$
atomic mass unit (1u is equivalent to 931.5 MeV)	u	1.661×10^{-27}	kg

ALGEBRAIC EQUATION

quadratic equation $x = \dfrac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

ASTRONOMICAL DATA

Body	Mass/kg	Mean radius/m
Sun	1.99×10^{30}	6.96×10^{8}
Earth	5.97×10^{24}	6.37×10^{6}

GEOMETRICAL EQUATIONS

arc length	$= r\theta$
circumference of circle	$= 2\pi r$
area of circle	$= \pi r^2$
curved surface area of cylinder	$= 2\pi rh$
area of sphere	$= 4\pi r^2$
volume of sphere	$= \frac{4}{3}\pi r^3$

Particle Physics

Class	Name	Symbol	Rest energy/MeV
photon	photon	γ	0
lepton	neutrino	ν_e	0
		ν_μ	0
	electron	$e^\pm$	0.510999
	muon	$\mu^\pm$	105.659
mesons	π meson	$\pi^\pm$	139.576
		π^0	134.972
	K meson	$K^\pm$	493.821
		K^0	497.762
baryons	proton	p	938.257
	neutron	n	939.551

Properties of quarks

antiquarks have opposite signs

Type	Charge	Baryon number	Strangeness
u	$+\frac{2}{3}e$	$+\frac{1}{3}$	0
d	$-\frac{1}{3}e$	$+\frac{1}{3}$	0
s	$-\frac{1}{3}e$	$+\frac{1}{3}$	-1

Properties of Leptons

		Lepton number
Particles:	$e^-, \nu_e ; \mu^-, \nu_\mu$	$+1$
Antiparticles:	$e^+, \overline{\nu_e}, \mu^+, \overline{\nu_\mu}$	-1

Photons and energy levels

photon energy $E = hf = hc/\lambda$

photoelectricity $hf = \phi + E_{k\,(max)}$

energy levels $hf = E_1 - E_2$

de Broglie wavelength $\lambda = \frac{h}{p} = \frac{h}{mv}$

Waves

wave speed $c = f\lambda$ *period* $f = \frac{1}{T}$

first harmonic $f = \frac{1}{2l}\sqrt{\frac{T}{\mu}}$

fringe spacing $w = \frac{\lambda D}{s}$ *diffraction grating* $d \sin\theta = n\lambda$

refractive index of a substance s, $n = \frac{c}{c_s}$

for two different substances of refractive indices n_1 *and* n_2,

law of refraction $n_1 \sin\theta_1 = n_2 \sin\theta_2$

critical angle $\sin\theta_c = \frac{n_2}{n_1}$ for $n_1 > n_2$

Mechanics

moments moment $= Fd$

velocity and acceleration $v = \frac{\Delta s}{\Delta t}$ $a = \frac{\Delta v}{\Delta t}$

equations of motion $v = u + at$ $s = \left(\frac{u+v}{2}\right)t$

$v^2 = u^2 + 2as$ $s = ut + \frac{at^2}{2}$

force $F = ma$

force $F = \frac{\Delta(mv)}{\Delta t}$

impulse $F\,\Delta t = \Delta(mv)$

work, energy and power $W = F\,s\cos\theta$

$E_k = \frac{1}{2}m\,v^2$ $\Delta E_p = mg\Delta h$

$P = \frac{\Delta W}{\Delta t}, P = Fv$

$efficiency = \frac{useful\ output\ power}{input\ power}$

Materials

density $\rho = \frac{m}{V}$ *Hooke's law* $F = k\,\Delta L$

Young modulus $= \frac{\text{tensile stress}}{\text{tensile strain}}$ *tensile stress* $= \frac{F}{A}$

tensile strain $= \frac{\Delta L}{L}$

energy stored $E = \frac{1}{2}F\Delta L$

Electricity

current and pd	$I = \frac{\Delta Q}{\Delta t}$ $V = \frac{W}{Q}$ $R = \frac{V}{I}$
resistivity	$\rho = \frac{RA}{L}$
resistors in series	$R_T = R_1 + R_2 + R_3 + \ldots$
resistors in parallel	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$
power	$P = VI = I^2 R = \frac{V^2}{R}$
emf	$\varepsilon = \frac{E}{Q}$ $\varepsilon = I(R + r)$

Circular motion

magnitude of angular speed	$\omega = \frac{v}{r}$
	$\omega = 2\pi f$
centripetal acceleration	$a = \frac{v^2}{r} = \omega^2 r$
centripetal force	$F = \frac{mv^2}{r} = m\omega^2 r$

Simple harmonic motion

acceleration	$a = -\omega^2 x$
displacement	$x = A \cos(\omega t)$
speed	$v = \pm \omega \sqrt{(A^2 - x^2)}$
maximum speed	$v_{max} = \omega A$
maximum acceleration	$a_{max} = \omega^2 A$
for a mass-spring system	$T = 2\pi \sqrt{\frac{m}{k}}$
for a simple pendulum	$T = 2\pi \sqrt{\frac{l}{g}}$

Thermal physics

energy to change temperature	$Q = mc\Delta\theta$
energy to change state	$Q = m\,l$
gas law	$pV = nRT$ $pV = NkT$
kinetic theory model	$pV = \frac{1}{3} N m (c_{\mathrm{rms}})^2$
kinetic energy of gas molecule	$\frac{1}{2} m (c_{\mathrm{rms}})^2 = \frac{3}{2} kT = \frac{3RT}{2N_A}$

Gravitational fields

force between two masses	$F = \frac{Gm_1 m_2}{r^2}$
gravitational field strength	$g = \frac{F}{m}$
magnitude of gravitational field strength in a radial field	$g = \frac{GM}{r^2}$
work done	$\Delta W = m\Delta V$
gravitational potential	$V = -\frac{GM}{r}$
	$g = -\frac{\Delta V}{\Delta r}$

Electric fields and capacitors

force between two point charges	$F = \frac{1}{4\pi\varepsilon_0} \frac{Q_1 Q_2}{r^2}$
force on a charge	$F = EQ$
field strength for a uniform field	$E = \frac{V}{d}$
work done	$\Delta W = Q\Delta V$
field strength for a radial field	$E = \frac{1}{4\pi\varepsilon_0} \frac{Q}{r^2}$
electric potential	$V = \frac{1}{4\pi\varepsilon_0} \frac{Q}{r}$
	$E = \frac{\Delta V}{\Delta r}$
capacitance	$C = \frac{Q}{V}$
	$C = \frac{A\varepsilon_0 \varepsilon_r}{d}$
capacitor energy stored	$E = \frac{1}{2} QV = \frac{1}{2} CV^2 = \frac{1}{2} \frac{Q^2}{C}$
capacitor charging	$Q = Q_0(1 - e^{-t/RC})$
decay of charge	$Q = Q_0 e^{-t/RC}$
time constant	RC

Magnetic fields

force on a current	$F = BIl$
force on a moving charge	$F = BQv$
magnetic flux	$\Phi = BA$
magnetic flux linkage	$N\Phi = BAN\cos\theta$
magnitude of induced emf	$\varepsilon = N\frac{\Delta\Phi}{\Delta t}$ $N\Phi = BAN\cos\theta$
emf induced in a rotating coil	$\varepsilon = BAN\omega\sin\omega t$
alternating current	$I_{\mathrm{rms}} = \frac{I_0}{\sqrt{2}}$ $\quad V_{\mathrm{rms}} = \frac{V_0}{\sqrt{2}}$
transformer equations	$\frac{N_s}{N_p} = \frac{V_s}{V_p}$ $efficiency = \frac{I_s V_s}{I_p V_p}$

Nuclear physics

the inverse square law for γ radiation	$I = \frac{k}{x^2}$
radioactive decay	$\frac{\Delta N}{\Delta t} = -\lambda N,\ N = N_o e^{-\lambda t}$
activity	$A = \lambda N$
half-life	$T_{½} = \frac{\ln 2}{\lambda}$
nuclear radius	$R = R_0 A^{1/3}$
energy-mass equation	$E = mc^2$

OPTIONS

Astrophysics

1 astronomical unit = 1.50 × 10^{11} m

1 light year = 9.46 × 10^{15} m

1 parsec = 206265 AU = 3.08 × 10^{16} m
= 3.26 light year

Hubble constant, H = 65 km s^{-1} Mpc^{-1}

$$M = \frac{\textit{angle subtended by image at eye}}{\textit{angle subtended by object at unaided eye}}$$

in normal adjustment	$M = \frac{f_o}{f_e}$
Rayleigh criterion	$\theta \approx \frac{\lambda}{D}$
magnitude equation	$m - M = 5\log\frac{d}{10}$
Wien’s law	$\lambda_{\mathrm{max}} T = 2.9 \times 10^{-3}\ \mathrm{m\ K}$
Stefan’s law	$P = \sigma A T^4$
Schwarzschild radius	$R_s \approx \frac{2GM}{c^2}$
Doppler shift for v << c	$\frac{\Delta f}{f} = -\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$
red shift	$z = -\frac{v}{c}$
Hubble’s law	$v = Hd$

Medical physics

lens equations	$P = \frac{1}{f}$ $m = \frac{v}{u}$ $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$
threshold of hearing	$I_0 = 1.0 \times 10^{-12}\ \mathrm{W\ m^{-2}}$
intensity level	$intensity\ level = 10\log\frac{I}{I}$
absorption	$I = I_0 e^{-\mu x}$ $\mu_{\mathrm{m}} = \frac{\mu}{\rho}$
ultrasound imaging	$Z = p\,c$ $\frac{I_r}{I_i} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$
half-lives	$\frac{1}{T_E} = \frac{1}{T_B} + \frac{1}{T_P}$

Engineering physics

moment of inertia $I = \Sigma m r^2$

angular kinetic energy $E_k = \frac{1}{2} I \omega^2$

equations of angular motion

$$\omega_2 = \omega_1 + \alpha t$$

$$\omega_2{}^2 = \omega_1{}^2 + 2\alpha\theta$$

$$\theta = \omega_1 t + \frac{\alpha t^2}{2}$$

$$\theta = \frac{(\omega_1 + \omega_2)\, t}{2}$$

torque $T = I\,\alpha$

$T = F\,r$

angular momentum $\text{angular momentum} = I\omega$

angular impulse $T\Delta t = \Delta(I\omega)$

work done $W = T\theta$

power $P = T\omega$

thermodynamics $Q = \Delta U + W$

$W = p\Delta V$

adiabatic change $pV^\gamma = \text{constant}$

isothermal change $pV = \text{constant}$

heat engines

$$\textit{efficiency} = \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H}$$

$$\textit{maximum theoretical efficiency} = \frac{T_H - T_C}{T_H}$$

work done per cycle = area of loop

input power = calorific value × fuel flow rate

$$\textit{indicated power} = (\textit{area of } p - V \textit{ loop}) \times (\textit{number of cycles per second}) \times (\textit{number of cylinders})$$

output or brake power $P = T\omega$

friction power = indicated power – brake power

heat pumps and refrigerators

refrigerator: $COP_{\text{ref}} = \frac{Q_C}{W} = \frac{Q_C}{Q_H - Q_C}$

heat pump: $COP_{\text{hp}} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C}$

Turning points in physics

electrons in fields $F = \frac{eV}{d}$

$F = Bev$

$r = \frac{mv}{Be}$

$\frac{1}{2} mv^2 = eV$

Millikan's experiment $\frac{QV}{d} = mg$

$F = 6\pi\eta r v$

Maxwell's formula $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$

$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2meV}}$

special relativity $t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$

$l = l_0 \sqrt{1 - \frac{v^2}{c^2}}$

$E = mc^2 = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}}$

Electronics

resonant frequency $f_0 = \frac{1}{2\pi\sqrt{LC}}$

Q-factor $Q = \frac{f_0}{f_B}$

operational amplifiers: open loop $V_{\text{out}} = A_{\text{OL}}(V_+ - V_-)$

inverting amplifier $\frac{V_{\text{out}}}{V_{\text{in}}} = -\frac{R_f}{R_{\text{in}}}$

non-inverting amplifier $\frac{V_{\text{out}}}{V_{\text{in}}} = 1 + \frac{R_f}{R_1}$

summing amplifier $V_{\text{out}} = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \cdots\right)$

difference amplifier $V_{\text{out}} = (V_+ - V_-)\frac{R_f}{R_1}$

Bandwidth requirement:

for AM $\text{bandwidth} = 2f_M$

for FM $\text{bandwidth} = 2(\Delta f + f_M)$

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All relevant information has been credited in the document.

This document has been produced for educational purposes only.

This document has been produced for the AQA A Level Physics Specification.

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Only constructive and reasoned feedback will be considered.