2023

PapaCambridge

Electricity

[Unit 9]

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Electric Current

As we know, atoms are made up of neutrons, protons, and electrons.

Electrons are the negatively charged particles which orbit the nucleus (made up of protons and neutrons).

The **unit of charge is Coulomb** & the **charge of an electron is -1.6×10^{-19}C.**

Ions – A Recap

Usually, the **positively and negatively charged particles (protons and electrons) are equal in an atom meaning there is no overall charge.**

However, there are times when there is **an imbalance.**
When this is the case, we **call it an ion** (not an atom).

A **positive ion is an ion with more protons than electrons.**

A **negative ion is an ion with more electrons than protons.**

The Charge of an Electron is Quantised

When an experiment was conducted to determine the charge of an electron **using charged oil droplets.**

The result showed that it seemed to only **occurred in integer multiples of a certain value**, this value was considered to be the charge of an electron.

Explaining Current

Metals, are made of atoms.

In the metal, **electrons move freely.**

When the battery (also made of metal) is connected to a circuit, the **electrons are attracted to the positive terminal which causes it to flow and cause an electrical current.**

Obviously, the **charge carriers are not always electrons,** they change from object to object.

For example, the charge carriers in a solution of plasma would be positive and negative ions.

So, what is Current?

The **electric current is the amount of charge flowing through a point in the electric circuit per second.**

The **unit of current is Amperes (A).**

The formula of current is:

$$Charge = Current \times Time$$

$$Q = I \times t$$

Note: To find current, we can simply rearrange the formula to make current (I) the subject.

Now that we have the formula, we should also know that **1 C = 1 As** which translates to **1 Coulomb = 1 Ampere Second.**

This is simply taken from the formula **Q = It.**

Conventional & Electron Current

Long ago, when we didn't know about electrons, we **assumed that the flow of current was from the positive to the negative node.**

This was assumed so that we can deepen our understanding of electricity (actually explore the more complex concepts).

As time went on, **we found out that the current actually goes from negative to positive.**

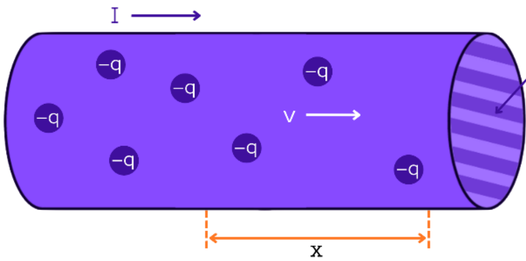
But it was too late, we couldn't change all of physics because of this.

So, we decided to **keep taking the current from positive to negative.**

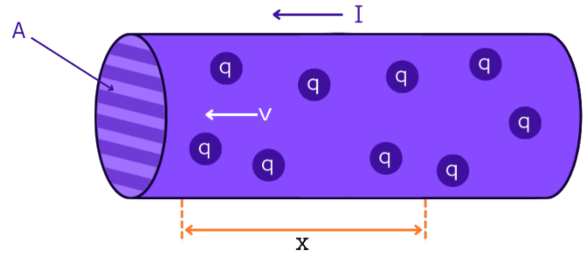
This is called the "conventional current".

When we take the **actual direction** (negative to positive), this is the **"electron current".**

Conduction in a Current-Carrying Conductor



Negative charge carriers when we take electron current.



Positive charge carriers when we take conventional current.

Where:
"q" is the charge carrier
"v" is the drift speed
"x" is the length of wire we look at
"I" is the current

Formula

There is a formula we should know when a question gives us all of this info.

$$I = A \times n \times v \times q$$

Where:
"q" is the charge carrier
"v" is the drift speed
"A" is the cross-sectional area of
"n" number density of charge carriers.
"I" is the current

Note: Most questions which give us quantities in this formula always have some trickery with the powers and conversions of units.
So, to score the marks be thorough with the conversions.

Derivation

1. To **calculate for current**, we can use the formula:

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

2. First, we must find **Q which is the total charge**.
   To do this, we can find the **total electrons present in the volume which gives us:**

$$A \times L \times n$$

   Now, we can find **Q by multiplying by the charge**:

$$Q = A \times L \times n \times q$$

3. Now, we can **find the formula for t.**
   To do this, we can find **v using the formula:**

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

4. We can then **rearrange for t:**

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

5. Now, **substitute t** into the formula:

$$I = \frac{Q}{t} = \frac{A \times L \times n \times q}{\frac{L}{v}} = A \times L \times n \times q \times L^{-1} \times v$$

6. To explain this, we basically **took the formula we derived for Q** and **divided it by the rearranged formula for t.**
   Now, we can simplify:

$$I = A \times n \times q \times v$$

Potential Difference & Power

To put it in perspective, **potential difference is the difference across the negative and positive nodes of a cell or component.**

The **potential difference refers to the energy transferred per unit charge that passes through a resistor and is measured in volts.**

Formula for Potential Difference

$$Potential\ Difference = \frac{Energy\ Transferred}{Charge} \qquad V\ (Volts) = \frac{W\ (Joules)}{Q\ (Coulombs)}$$

Note: Energy Transferred can also be called "Work Done" in this case.

The **unit for potential difference is volts but it can also be JC^{-1}.**

Electrical Power

Power is the rate of work done or of transferring energy.

One of the most important formulas we should know is:

$$P = I \times V$$

Derivation

1. We can start **by writing the original formula for power:**

$$P = \frac{Work\ Done}{t}$$

2. We also know that **V can be work done over charge.**

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

3. Now, **rearrange the voltage formula for W and substitute into power formula:**

$$W = VQ$$

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

4. We know that **Q/t is current hence:**

$$P = VI$$

More Formulas!

We can use the **power formula and get 2 more formulas:**

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

Resistance & Resistivity

Resistance

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

This gives us the formula:

$$Resistance = \frac{Voltage}{Current} \qquad R = \frac{V}{I}$$

This formula allows us to see the relationships between resistance, voltage, and current:

$$Resistance \propto Voltage \qquad Resistance \propto \frac{1}{Current}$$

A resistor is a **device which has resistance to the flow of electric current.**

Electrical Heating

Joule heating is the **heating effect which occurs when an electric current is passed through a resistor.**

This is because when we pass current through a resistor, its temperature increases.

Ohm's Law

Ohm's law states **that the current in a metallic conductor is proportional to the potential difference across it given that the conductor is at a constant temperature.**

A wire for example, shows this in action as the I-V graph produced is straight.

A filament lamp shows this as well because as the current increases, so does its temperature and hence the two quantities are no longer proportional.

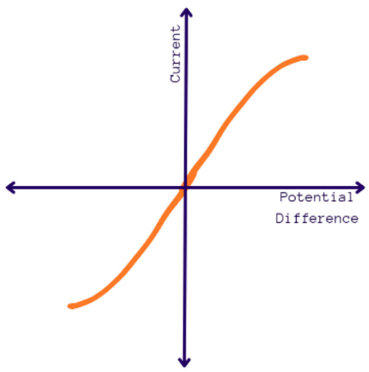
Current-Voltage (I-V) Characteristics

There are 2 graphs we will look at:

1. Graph of Lamp
2. Graph of Wire
3. Graph of Diode

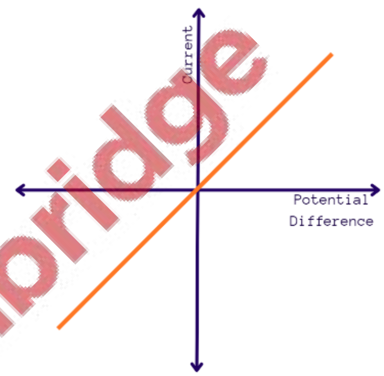
Filament Lamp

As seen in the graph, the **resistance is constant at first** until it **reaches a point where it starts to curve and its gradient increases.**



Wire

As seen in the graph, there is a **straight line going through the origin** meaning that the **current is directly proportional to potential difference.**



Diode

A **diode** is a **semiconductor device which only conducts electricity in one direction.**

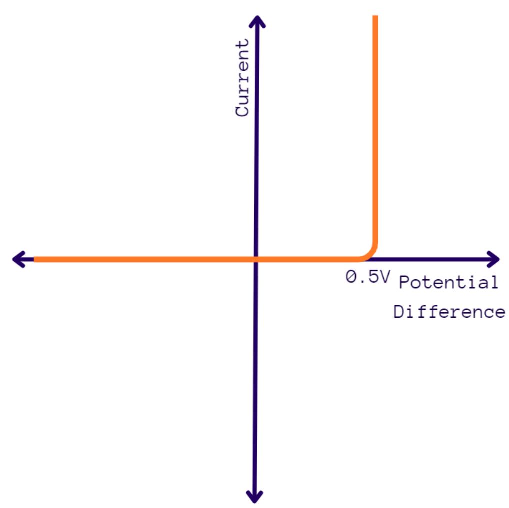
"forward bias" is the **condition in a diode where the application of a voltage allows it to conduct a current in the direction of the arrowhead.**

"reverse bias" is the **condition where the diode will not conduct when the voltage is in the opposite direction to the arrowhead.**

As seen on the right, the diode does not obey Ohm's law.

This is **because the properties of a semiconductors are different to a conductor.**

This results in a graph which shows that **R is not constant**, the **current and voltage are not proportional**, and hence **diodes do not follow Ohm's law.**



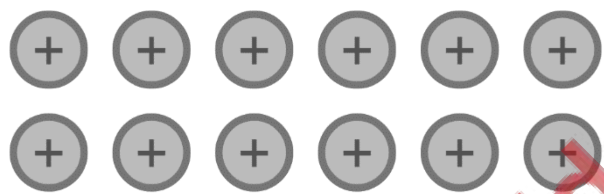
Resistivity

Restivity is a **property of a certain material that indicates how strongly it resists the flow of electric current;** it is a **constant for that material at a particular temperature.**

The **unit for resistivity is Ωm^{-1}**

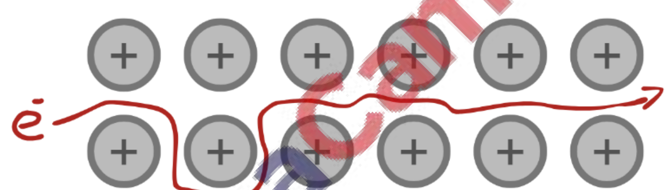
Wires on a Molecular Level

Let's zoom into a metal wire, we see a **bunch of positive metal ions arranged in a lattice like so:**



Another thing we should know is that these **metal ions are vibrating around a fixed point.**

The electron must **go through this lattice and come out the other side.**

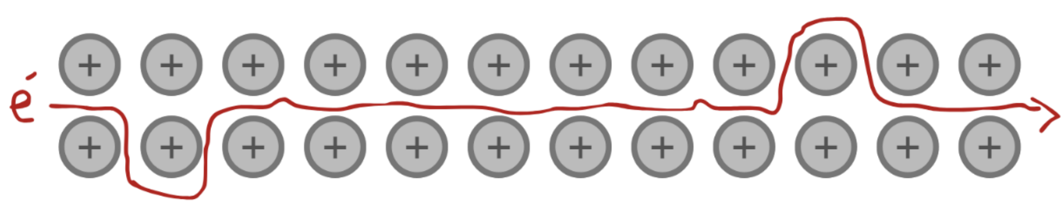


As the electron passes, **it must overcome the forces of attraction from the metal cations.**
This slows the electron down or **"resists" the motion.**

Relationships

Resistance & Length

If we increase the length of the wire, we see:



Again, the **metal cations attract the electron which opposes its motion.**

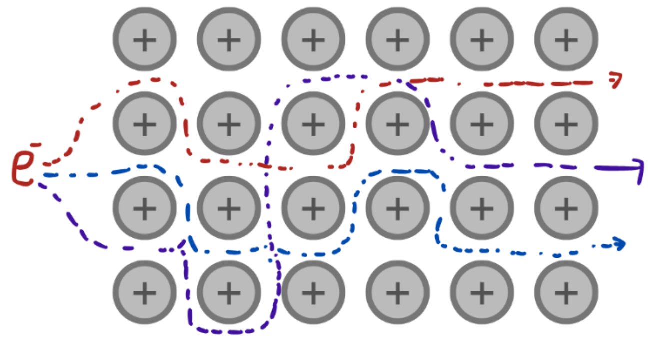
Since this **happens more often, the resistance increases.**

Hence, the relationship is:

$$R \propto L$$

Resistance & Cross-sectional Area

If we increase the cross-sectional area of the wire, the **thickness increases and so the size of the lattice does too.**



In the above diagram, the **electron can take many different paths** which means that it will obviously take the one with the lowest resistance.

As we increase the cross-sectional area, there is a **higher chance that the resistance decreases.**

Hence, we show this relationship like so:

$$R \propto \frac{1}{A}$$

Adding one and one

Now, if we combine the two relations we get:

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

We can **introduce the constant of proportionality (ρ) to get:**

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

Here, the **constant of proportionality is actually the resistivity.**

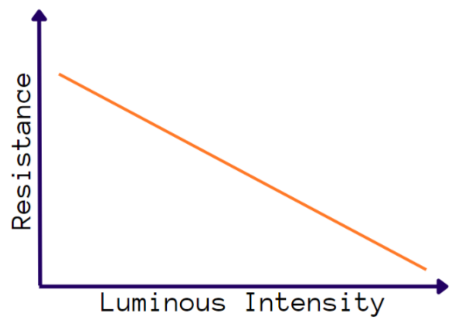
Light Dependent Resistors (LDR) & Thermistors

Light Dependent Resistor (LDR)

A light dependent resistor or LDR is a **type of resistor where the resistance decreases as the intensity of the light falling on it increases.**

This is because of the semiconductor's special properties (not needed to know).

R vs l_v for LDR



As luminous intensity increases, resistance decreases.

Note: The relationship is not inversely proportional!

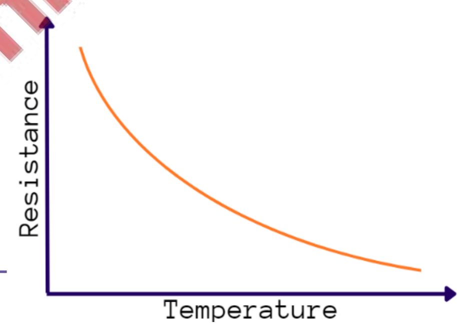
Thermistor

A thermistor is a **type of resistor where the resistance decreases as the temperature (of the component) increases.**

In reality, there are thermistors where the resistance increases when temperature increases (positive temperature coefficient).

However, we will **always assume that the thermistor has a negative temperature coefficient** meaning that the resistance decreases as the temperature increases.

R vs T for Thermistor



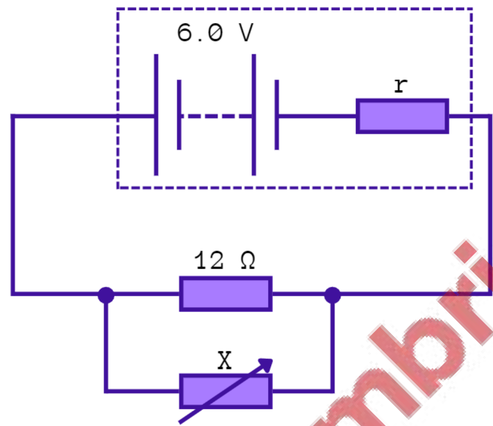
This variation is non-linear but is almost exponential over a range of temperatures.

Past Paper Questions

Question 1 [9702/22/F/M/17 Q6b ii]

Context:

A battery of electromotive force (e.m.f.) 6.0V and internal resistance r is connected to a resistor of resistance 12Ω and a variable resistor X, as shown in Fig. 6.2.



Question:

A charge of 2.5kC passes through the battery.

Calculate

1. **The total energy transformed by the battery.**

$$V = \frac{W}{Q}$$
$$W = VQ$$
$$W = 2.5 \times 10^3 \times 6$$
$$W = 15000\,J$$

Question 2 [9702/12/O/N/19 Q32]

A fixed resistor of resistance 12Ω is connected to a battery. There is a current of 0.20A in the resistor. The current is now doubled.

What is the new power dissipated in the resistor?

A. 0.48W **B. 0.96W** **C. 1.9W** **D. 4.8W**

Explanation:

$$P = I^2R$$
$$P = (0.4)^2 \times 12$$
$$P = 1.92W$$

Question 3 [9702/12/F/M/19 Q17]

The data below are taken from a test of a petrol engine for a motor car.

Power Output	**150 kW**
Fuel Consumption	**20 liters per hour**
Energy Content of Fuel	**40 MJ per liter**

What is the ratio $\frac{Power\ Output}{Power\ Input}$?

A. $\frac{150 \times 10^3}{40 \times 10^6 \times 20 \times 20 \times 60}$ **B.** $\frac{150 \times 10^3 \times 60 \times 60}{40 \times 10^6 \times 20}$ **C.** $\frac{150 \times 10^3 \times 40 \times 10^6 \times 20}{60 \times 60}$ **D.** $\frac{150 \times 10^3 \times 20}{40 \times 10^6 \times 60 \times 60}$

Explanation:

The power input requires the rate and the actual work done.

Since that is the case, we require the fuel consumption (the rate) and multiply it with the energy content (work done).

We also need it in the simplest unit which would be like so:

$$Power\ Input = 40 \times 20$$
$$Power\ Input = 20 \times 40 \times 10^6$$

Since we take the rate as hours, we must convert the watts to hours as it is joules per second.

Hence:

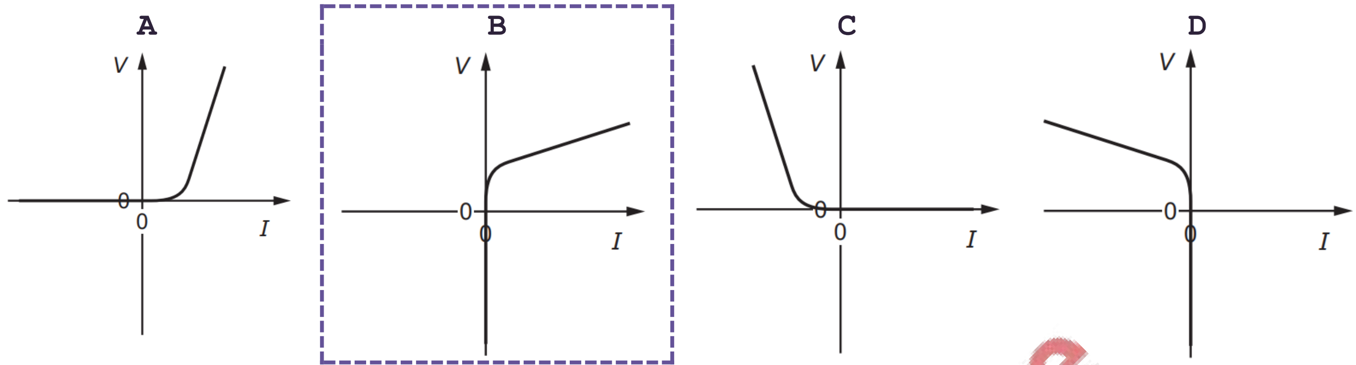
$$150 \times 10^3 \times 60 \times 60$$

This gives us:

$$\frac{150 \times 10^3 \times 60 \times 60}{20 \times 40 \times 10^6}$$

Question 4 [9702/12/M/J/18 Q33]

Which graph shows the variation of voltage V with current I for a semiconductor diode?



Explanation:

As we know, the variation for a semiconductor diode looks similar to A.

However, that is when it is current plotted against voltage.

Here, is it voltage against current and hence it is not C or A.

We also do not choose D as it shows current to be negative (not conventional) so we prefer B.

Question 5 [9702/11/O/N/17 Q34]

A filament lamp has a resistance of 180Ω when the current in it is 500mA.
What is the power dissipated in the lamp?

A. 45W	**B. 90W**	**C. 290W**	**D. 360W**

Explanation:

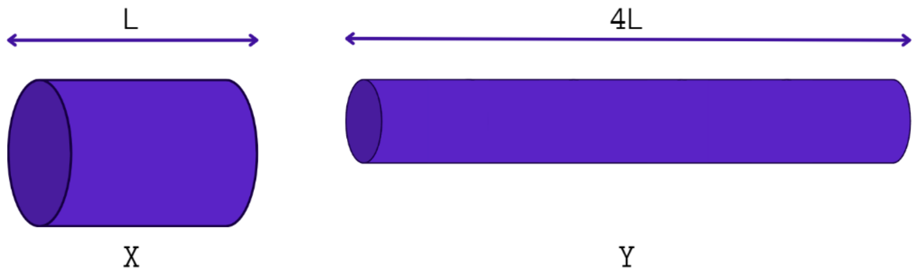
Use the formula $P = I^2 R$:

$$I = \frac{500}{1000} = 0.5A$$

$$P = (0.5)^2 \times 180 = 45W$$

Question 6 [9702/11/O/N/17 Q35]

Two copper wires X and Y have the same volume. Wire Y is four times as long as wire X.



What is the ratio $\frac{\textbf{Resistance of Wire Y}}{\textbf{Resistance of Wire X}}$?

A. 1 **B. 4** **C. 8** **D. 16**

Explanation:

Use the equation $R = \frac{\rho L}{A}$.

Let's take some random values for volume and length:

$$L = 2$$
$$V = 16$$

Now, since the material is same, we cancel out ρ,

Let's find the areas for both wires:

X

$$16 = 2 \times A$$
$$A = 8$$

Y

$$16 = (4 \times 2) \times A$$
$$A = 2$$

Stick this into the equation and find R for both:

X

$$R = \frac{2}{8} = 0.25$$

Y

$$R = \frac{8}{2} = 4$$

Use these values to get a ratio:

$$Ratio = \frac{4}{0.25} = 16$$

Sources (and Resources) Used

Most of the information has come from the **AS & A Level Physics Student Book by Hodder Education**.

Other resources/tools have also been used and are listed below:

Name	Link	Use
Save My Exams	**LINK**	Mainly understanding concepts to make them simpler
ZNotes	**LINK**	
Canva	**LINK**	Designing of figures and diagrams
AS/A Level Syllabus	**LINK**	Checking syllabus

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Physics