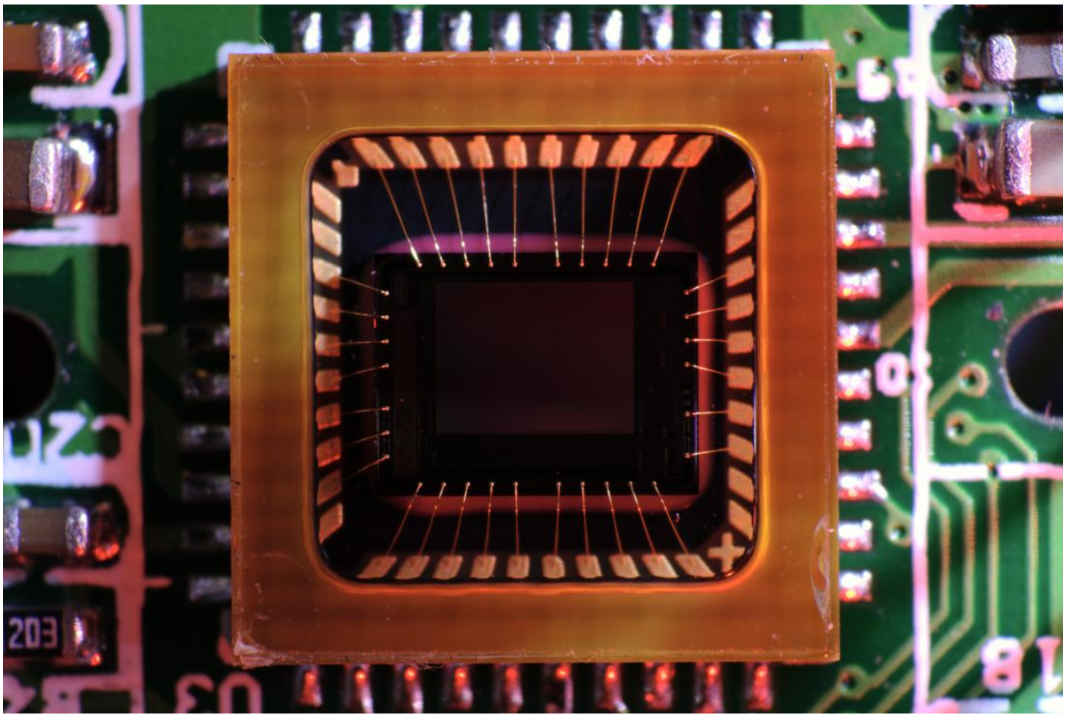
Higher Physics
Electricity
Notes



Teachers Booklet

Learning Outcomes – Monitoring and measuring a.c.

This builds on information from
Electricity and Energy booklet 1: Electrical charge carriers and fields.

At the end of this section you should be able to

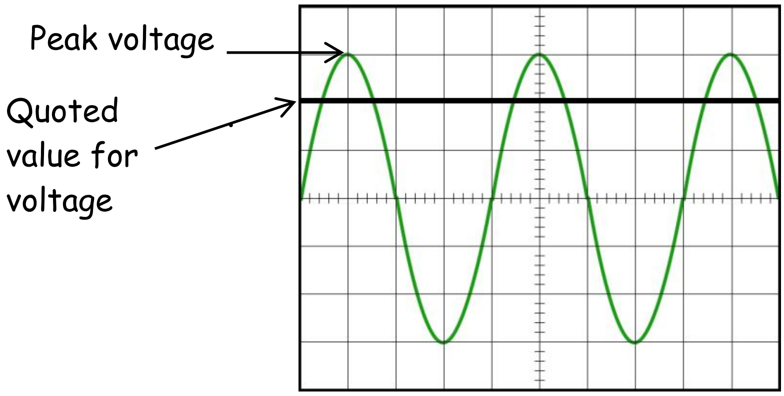
- Describe alternating current (a.c.) as a current which changes direction and instantaneous value with time.
- Identify the peak voltage on an oscilloscope screen.
- Measure the peak voltage using an oscilloscope
- Measure the r.m.s. voltage using a voltmeter
- State the relationship between the peak and the r.m.s. values for a sinusoidally varying voltage and current.
- Carry out calculations involving peak and r.m.s. values of voltage and current.
- Measure the frequency of an ac signal on an oscilloscope screen.
- State the relationship between current and frequency in a resistive circuit.

Revision

Direct current flows in one direction and has one value.

Direct current is supplied by a battery or a d.c. power supply.

Alternating Current – Calculating Peak Values



Alternating current changes direction and instantaneous value with time.

When the wave is displayed on an oscilloscope screen you see a sine wave.

To measure the peak voltage

1. Count the number of squares either from the centre to the top of the wave OR from bottom to top of the wave and divide by two.
2. Look at the y-gain setting on the oscilloscope.
3. Multiply the number of squares by the y-gain setting to calculate the peak voltage.

To measure the frequency of the alternating current

1. Count the number of squares for one complete wave.
2. Check the time-base setting on the oscilloscope.
3. Multiply the number of squares by the time-base setting to calculate the period of the wave (T).
4. The frequency of the wave is calculated using

$$f = \frac{1}{T}$$

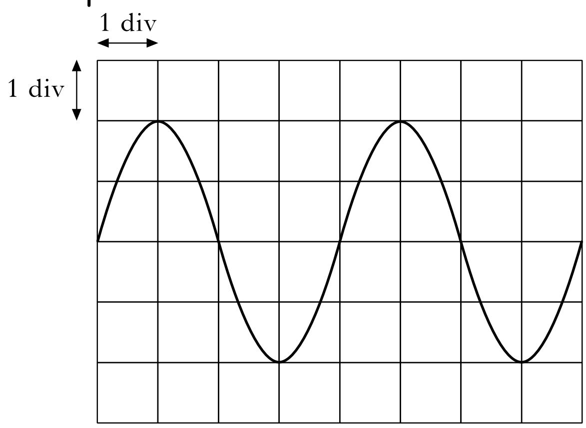
Where T = period (seconds – s)
f = frequency (Hertz – Hz)

If the voltage is measured with an a.c. voltmeter the value obtained is lower than the peak value displayed on an oscilloscope.

Mains voltage is 230 V a.c. at 50Hz.

Alternating Current – Calculating Peak Values

Example 1



The diagram shows the trace on an oscilloscope when an alternating voltage is applied to its input. The timebase is set at 5 ms/div and the Y-gain is set at 10 V/div.
Which row in the table gives the peak voltage and the frequency of the signal?

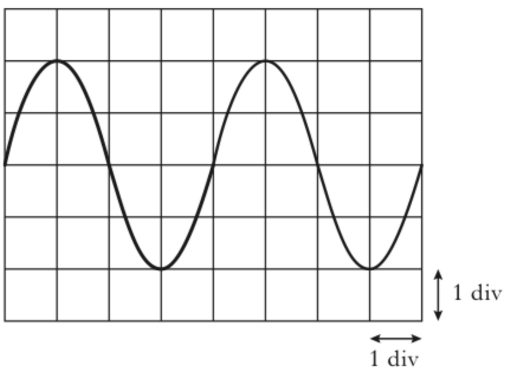
	Peak voltage/V	Frequency/Hz
A	7.1	20
B	14	50
C	20	20
D	20	50
E	40	50

$\boxed{D}$

SQA H Physics 2008 Q10

Example 2

An oscilloscope is connected to the output terminals of a signal generator.
The trace displayed on the screen is shown below.
The timebase of the oscilloscope is set at 30 ms/div.



Calculate the frequency of the output signal from the signal generator.

One complete wave = 4 squares.
Period of wave = 4 x 30 ms = 120 ms.

$$f = \frac{1}{T} = \frac{1}{120\ x\ 10^{-3}} = 8.3\ Hz$$

SQA 2014 (revised) Q 15 adapted

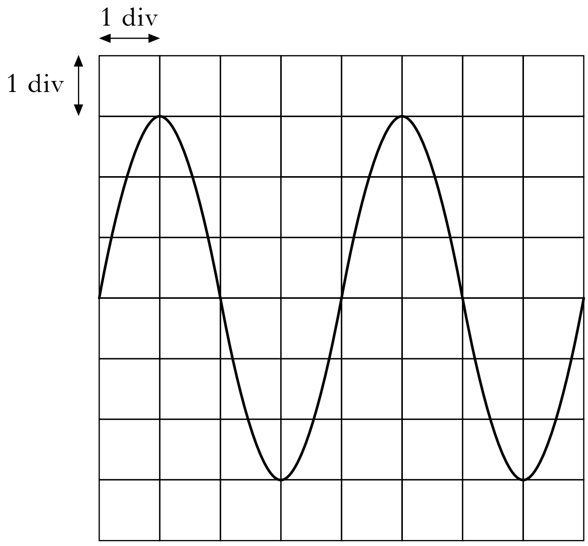
Alternating Current – Calculating Peak Values

Since the value for current in a.c. is continuously changing we use an average value when comparing it to d.c. This is called the root mean square (r.m.s.) value.

$$V_{pk} = \sqrt{2}\, V_{rms} \qquad\qquad I_{pk} = \sqrt{2}\, I_{rms}$$

Where V_{pk} = Peak voltage (V)
V_{rms} = Root mean square voltage (V)
I_{pk} = Peak Current (A)
I_{rms} = Root mean square Current (A)

Example 3
The signal from a power supply is displayed on an oscilloscope. The trace on the oscilloscope is shown below.



The time-base is set at 0.01 s/div and the Y-gain is set at 4.0 V/div.
Calculate a) the r.m.s. voltage and
b) the frequency of the signal.

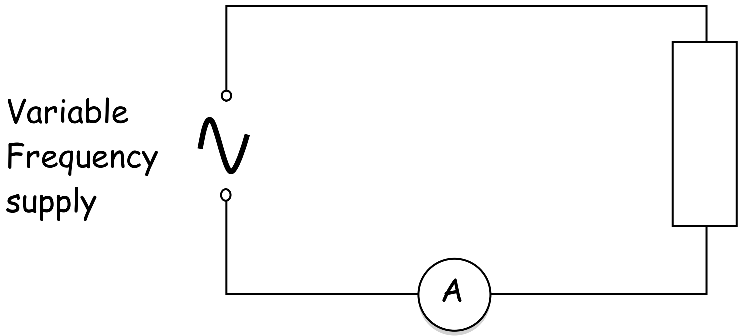
a) V_{pk} = 3 x 4 = 12V $\qquad V_{rms} = \frac{V_{pk}}{\sqrt{2}} = \frac{12}{\sqrt{2}}$ = 8.5V

b) T = 4 x 0.01 = 0.04s

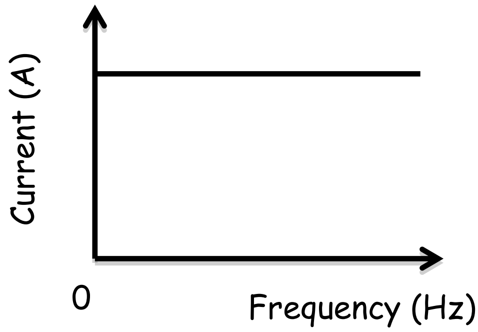
$$f = \frac{1}{T} = \frac{1}{0.04} = 25\text{Hz}$$

SQA H 2007 Q10 adapted

Alternating Current and Resistance

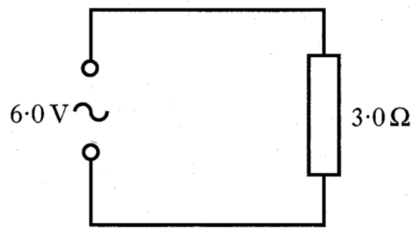


The relationship between current and frequency is determined using the circuit shown above. The current is measured as the frequency is increased.



As the frequency increases the current remains constant through a resistor.

Example 4
A supply with a sinusoidally alternating output of 6.0 V r.m.s. is connected to a 3.0 Ω resistor.



Calculate the peak voltage across the resistor and the peak current in the circuit?

Vpk = $\sqrt{2}$ Vrms = $\sqrt{2}$ x 6 = 8.5 V

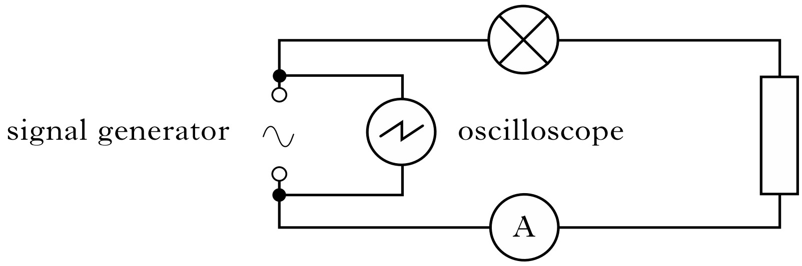
Ipk = $\sqrt{2}$ Irms = $\sqrt{2}$ x $\frac{V_{rms}}{R}$ = $\sqrt{2}$ x $\frac{6}{3}$ = 2.8A

SQA H 2001 Q 10 adapted

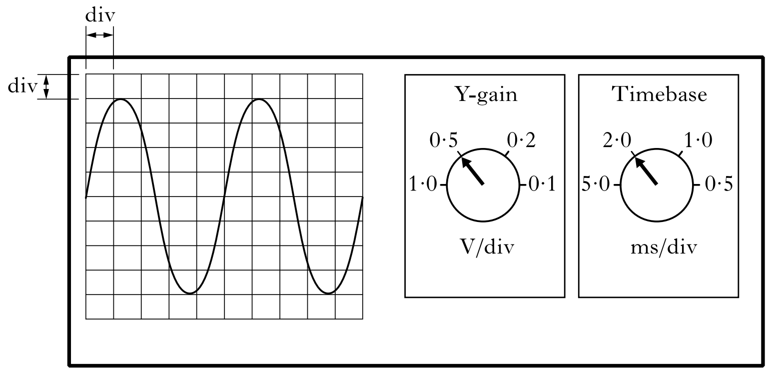
Alternating Current

Example 5

A signal generator is connected to a lamp, a resistor, and an ammeter in series. An oscilloscope is connected across the output terminals of the signal generator.



The oscilloscope control settings and the trace on its screen are shown



(a) For this signal calculate:
  i. The peak voltage;
  ii. The frequency

(b) The frequency is now doubled. The peak voltage of the signal is kept constant. State what happens to the reading on the ammeter.

(a) i. Vpk = 4 x 0.5 = 2V
  ii. T = 5 x 2 = 10 ms
  $f = \frac{1}{T} = \frac{1}{10\ x\ 10^{-3}}$ = 100 Hz

(b) The current stays the same (since frequency does not affect current through a resistor).

SQA H 2010 Q 26

Electricity Problem Booklet
P7 Q 1 - 6

Learning Outcomes – Current, Potential Difference, Power and Resistance

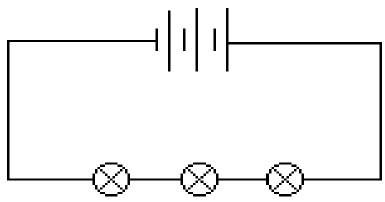
This builds on information from
Electricity and Energy booklet 2: Practical Electrical and Electronic Circuits
Ohm's Law

At the end of this section you should be able to

- state that in a series circuit the current is the same at all positions.
- state that the sum of the potential differences across the components in series is equal to the voltage of the supply.
- state that the sum of the currents in parallel branches is equal to the current drawn from the supply.
- state that the potential difference across components in parallel is the same for each component.
- carry out calculations involving the relationship $V = IR$.
- carry out calculations involving the relationships $R_T = R_1 + R_2 + R_3$ and $1/R_T = 1/R_1 + 1/R_2 + 1/R3$.
- state that when there is an electrical current in a component, there is an energy transformation.
- state the relationship between energy and power, $E = Pt$
- state that the electrical energy transformed each second = IV.
- carry out calculations using $P = IV$ and $E = Pt$.
- explain the equivalence between $P = IV$, $P = I^2R$ and $P = V^2/R$.
- carry out calculations involving the relationships between power, current, voltage and resistance.
- state that a potential divider circuit consists of a number of resistors, or a variable resistor, connected in series across a supply.
- carry out calculations involving potential differences and resistances in a potential divider.

Revision – Ohm's Law and Resistance

1. Series Circuits



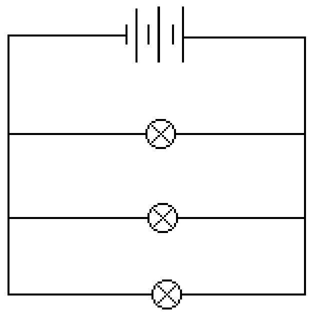
The current in a series circuit is the same at all points.

$I_1 = I_2$

The supply voltage is equal to the sum of the voltage drops.

$V_S = V_1 + V_2 + V_3$

2. Parallel Circuits



The current from the supply is equal to the sum of the current in all the branches.

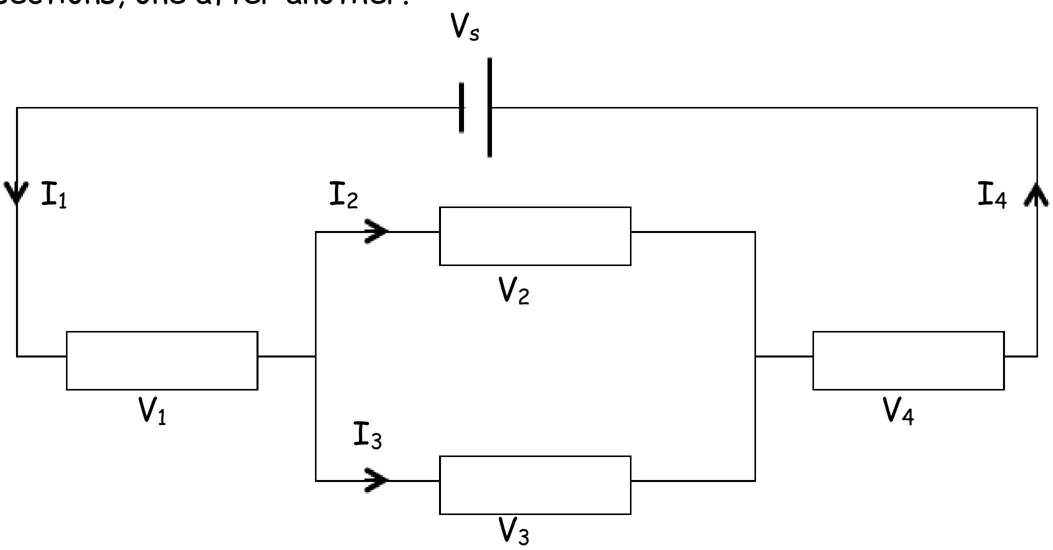
$I_s = I_1 + I_2 + I_3$

The voltage across each component in parallel with the supply is the same.

$V_s = V_1 = V_2 = V_3$

3. Complex Circuits

A complex circuit is a combination of both series and parallel elements. This can be analysed by breaking it down into series and parallel sections, one after another.



In this circuit $I_1 = I_4 = I_2 + I_3$

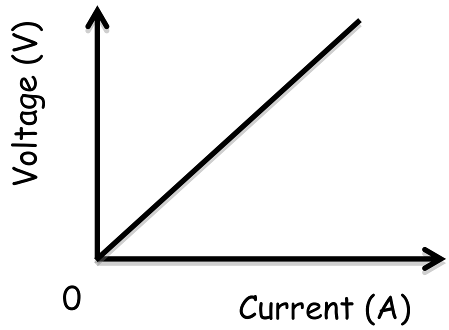
and $V_2 = V_3$

and $V_s = V_1 + V_2 + V_4$

Revision – Ohm's Law and Resistance

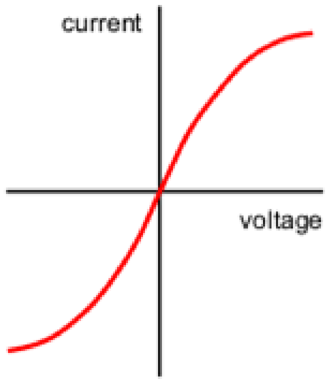
$V = IR$

V = Voltage (Volts – V)
I = Current (Amperes – A)
R = Resistance (Ohms – Ω)

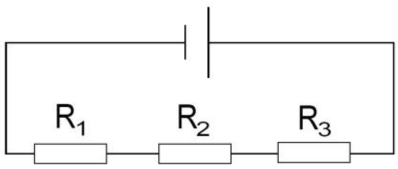


The graph of potential difference versus current for a resistor is a straight line graph passing through the origin.

For non-ohmic devices such as the light emitting diode (LED) or filament lamp the graph is non-linear.

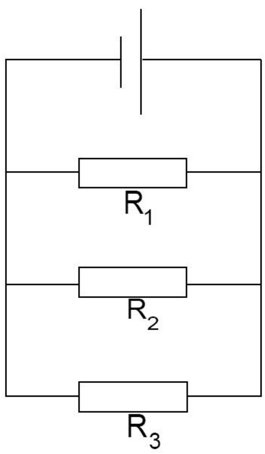


Series Resistance



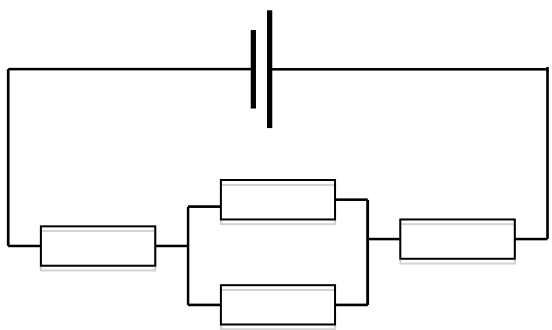
$R_T = R_1 + R_2 + R_3$

Parallel Resistance



$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Mixed Series and Parallel Resistance

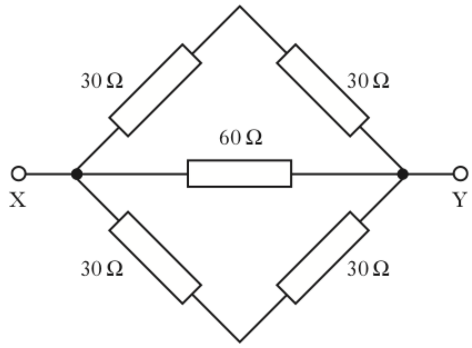


Calculate the value of resistor which would replace each section of the circuit until you can calculate the total resistance.

Revision – Ohm's Law and Resistance

Example 6

Five resistors are connected as shown.



The resistance between X and Y is

Calculate the two branches with series resistors first.

R_t = 30 + 30 = 60 Ω

Then calculate the three branches in parallel

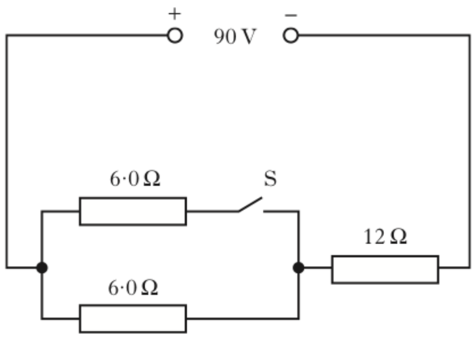
$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{60} + \frac{1}{60} + \frac{1}{60} = \frac{3}{60}$

$R_t = \frac{60}{3}$ = 20 Ω

SQA H 2014 revised Q 16

Example 7

A circuit is set up as shown.



The internal resistance of the supply is negligible.

Calculate the potential difference across the 12 Ω resistor when

a) switch S is open and
b) when switch S is closed.

a) Total resistance = 6 + 12 = 18 Ω
   I = V/Rt = 90/18 =5A
   V = IR = 12 x 5 = 60V
b) Total resistance of two 6 Ω resistors in parallel = 3 Ω
   Total resistance in circuit = 3 + 12 = 15 Ω
   I = V/Rt = 90/15 =6A
   V = IR = 12 x 6 = 72V

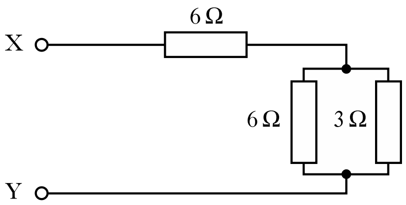
SQA H 2014 revised Q 17

Revision – Ohm's Law and Resistance

Example 8

Which of the following combinations of resistors has the greatest resistance between X and Y?

A

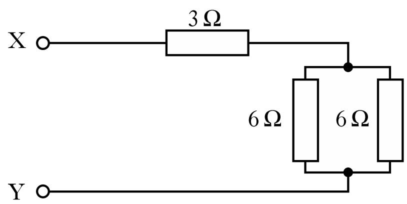


$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{6} + \frac{1}{3} = \frac{3}{6}$$

$R_t = \frac{6}{3} = 2\ \Omega$

Total resistance = 6 + 2 = 8 Ω

B

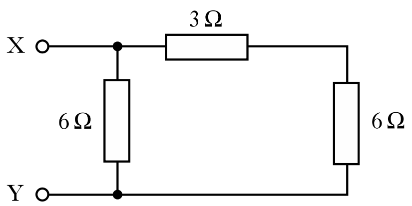


$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{6} + \frac{1}{6} = \frac{2}{6}$$

$R_t = \frac{6}{2} = 3\ \Omega$

Total resistance = 3 + 3 = 6 Ω

C

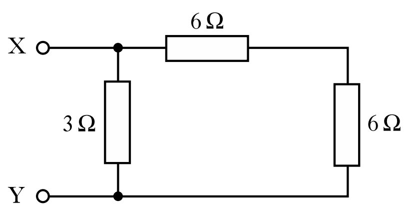


Resistance in series=3 + 6= 9Ω

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{6} + \frac{1}{9} = \frac{5}{18}$$

$R_t = \frac{18}{5} = 3.6\ \Omega$

D

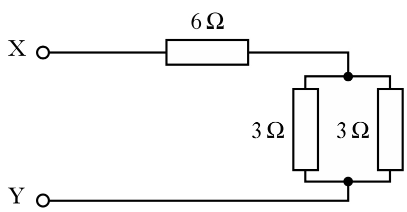


Resistance in series=6+6= 12Ω

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{3} + \frac{1}{12} = \frac{5}{12}$$

$R_t = \frac{12}{5} = 2.4\ \Omega$

E



$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{3} + \frac{1}{3} = \frac{2}{3}$$

$R_t = \frac{3}{2} = 1.5\ \Omega$

Total resistance = 6 + 1.5

= 7.5 Ω

Revision – Electrical Energy and Power

Where $E = Pt$

E = Energy (Joules – J)
P = Power (Watts – W)
t = time (seconds - s)

In electrical circuits we can also use

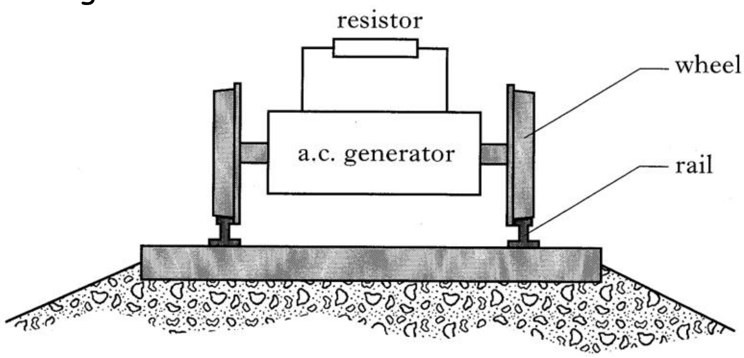
$$P = IV$$

Since V = IR and I = V/R we can substitute for V or for I in the equation

$P = IV = I \times IR \Rightarrow P = I^2 R$ $P = IV = V/R \times V \Rightarrow P = \frac{V^2}{R}$

Where P = Power (Watts – W)
I = Current (Amperes – A)
V = Voltage (Volts – V)
R = Resistance (Ohms – Ω)

Example 9
Part of a train braking system consists of an electrical circuit as shown in the diagram below.



While the train is braking, the wheels drive an a.c. generator which changes kinetic energy into electrical energy. This electrical energy is changed into heat in a resistor. The r.m.s. current in the resistor is 2.5×10^3A and the resistor produces 8.5 MJ of heat each second. Calculate the peak voltage across the resistor.

8.5 MJ/s = 8.5 MW

$P = I_{rms} V_{rms} \Rightarrow V_{rms} = P/I_{rms} = 8.5 \times 10^6/2.5 \times 10^3 = 3400$ V

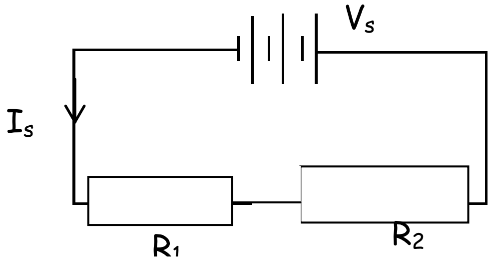
$V_{pk} = \sqrt{2}\, V_{rms} = \sqrt{2} \times 3400 = 4.8 \times 10^3$V

SQA H 2004 Q 22 (b)

Electricity Problem Booklet
P11 Q 9 - 15

Revision – Potential Dividers

A potential divider circuit uses two (or more) resistors to divide up the voltage or potential available across that part of the circuit.



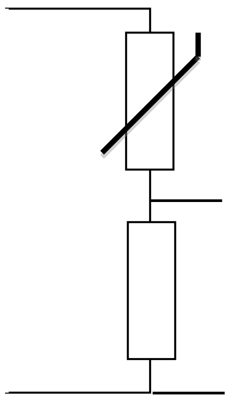
Total resistance in circuit = $R_1 + R_2$

Current in circuit = $\frac{V_S}{R_1+R_2}$

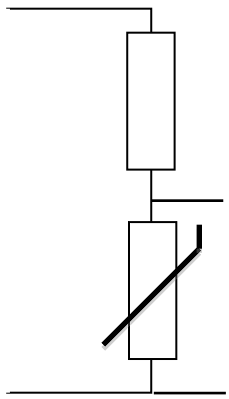
Voltage across R_1 = $\frac{V_S}{R_1+R_2} \times R_1$

Voltage across R_2 = $\frac{V_S}{R_1+R_2} \times R_2$

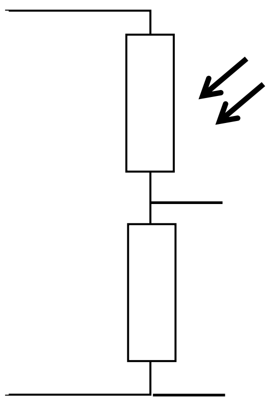
Voltage dividers are usually shown as a vertical circuit and may contain components which change resistance due to external conditions such as light or temperature (LDR and thermistor).



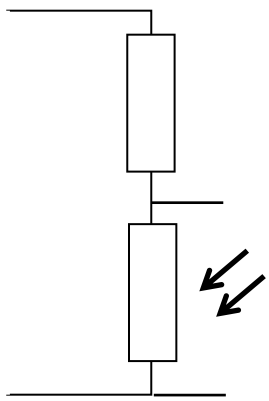
As temperature rises, output voltage increases.



As temperature rises, output voltage decreases.



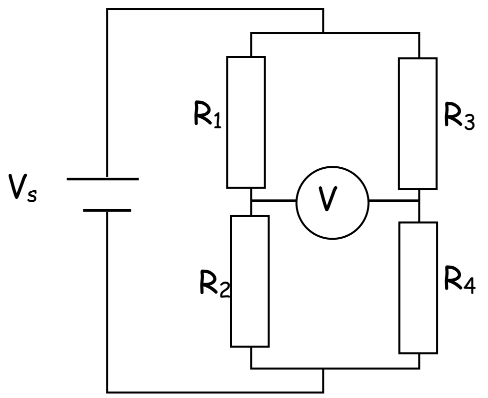
As light level rises, output voltage increases.



As light level rises, output voltage decreases.

Revision – Wheatstone Bridge

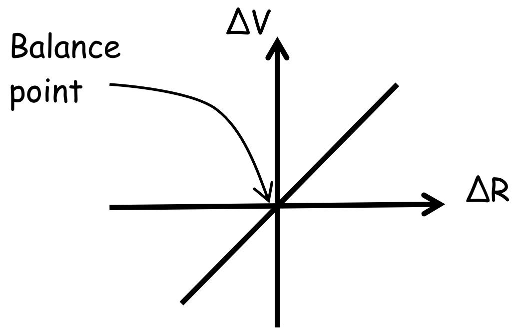
The Wheatstone bridge is really just two potential divider circuits which compare the output voltage of each circuit. It can be used to show changes in input conditions or to control other circuits.



In order for the voltmeter to read 0V the voltage on either side of the voltmeter must have the same value. The ratio of R_1:R_2 must be the same as R_3:R_4.
This is described as the bridge being balanced.

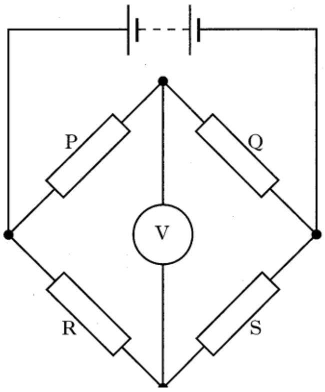
Balanced Wheatstone Bridge V = 0 or $\frac{R_1}{R_2} = \frac{R_3}{R_4}$ or $\frac{R_1}{R_3} = \frac{R_2}{R_4}$

The out of balance Wheatstone bridge can be used to measure <u>small</u> changes in resistance.



This is because $\Delta V \propto \Delta R$

Example 10
The diagram below shows a balanced Wheatstone bridge where all the resistors have different values.



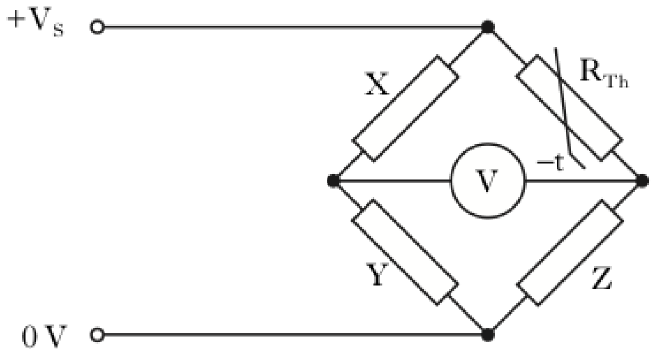
Which change(s) would make the bridge unbalanced?

I Interchange resistors P and S
<u>II Interchange resistors P and Q</u>
III Change the e.m.f. of the battery

SQA H 2002 Q9

Revision – Wheatstone Bridge

Example 11
A Wheatstone bridge is used to measure the resistance of a thermistor as its temperature changes.

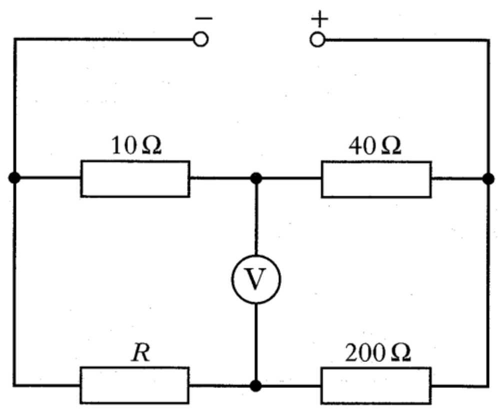


The bridge is balanced when X = 2.2 kΩ, Y = 5.0 kΩ and Z = 750Ω..
Calculate the resistance of the thermistor, R_{th}, when the bridge is balanced.

$\frac{R_1}{R_2} = \frac{R_3}{R_4}$ ➔ $\frac{2200}{5000} = \frac{R_{th}}{750}$ ➔ $R_{th} = \frac{2200 \ x \ 750}{5000} = 330\Omega$

SQA H 2007 Q27a

Example 12
The circuit diagram shows a balanced Wheatstone bridge.



The resistance of resistor R is

A 0.5 Ω
B 2.0 Ω
C 50 Ω
D 100 Ω
E 800 Ω

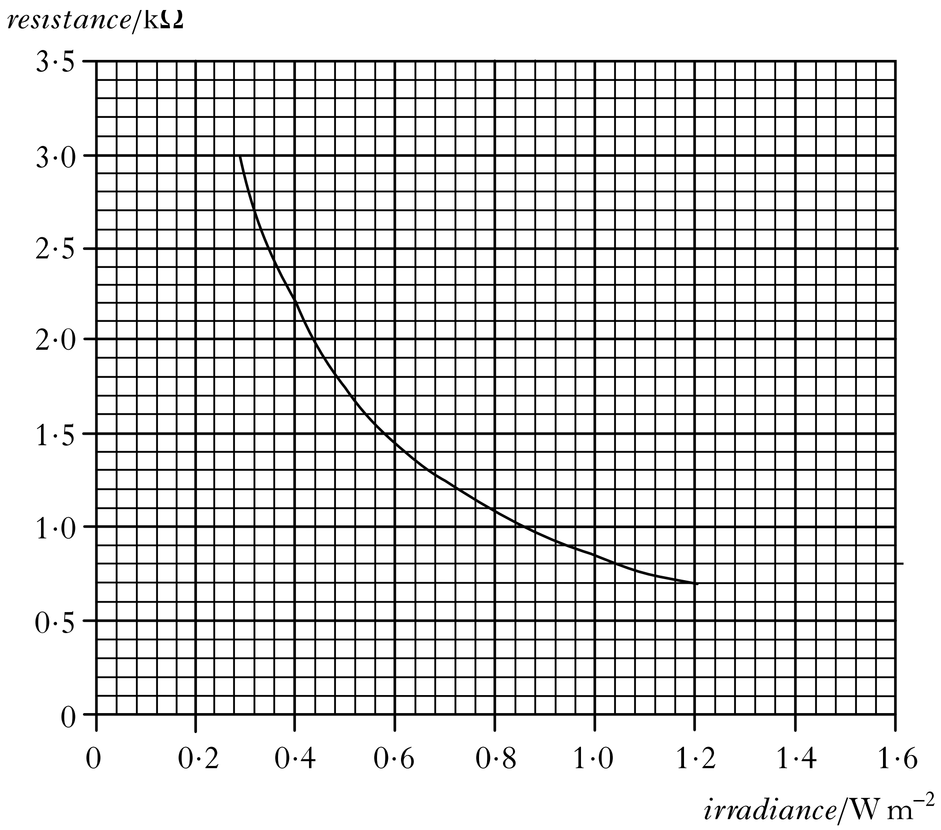
$\frac{R_1}{R_2} = \frac{R_3}{R_4}$ ➔ $\frac{10}{40} = \frac{R}{200}$

➔ $R_{th} = \frac{200 \ x \ 10}{40} = 50 \ \Omega$

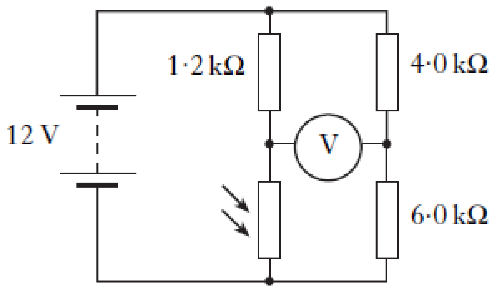
SQA H 2006 Q 10

Example 13

The graph shows how the resistance of an LDR changes with the irradiance of the light incident on it.



The LDR is connected in the following bridge circuit.



Determine the value of irradiance at which the bridge is balanced. Show clearly how you arrive at your answer.

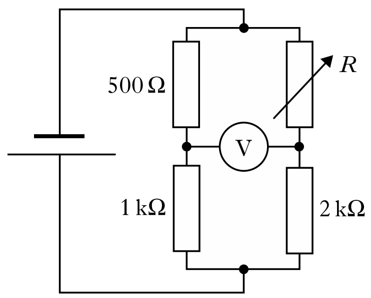
$\frac{R_1}{R_2} = \frac{R_3}{R_4}$ ➔ $\frac{1200}{4000} = \frac{R_{LDR}}{6000}$ ➔ $R_{LDR} = \frac{1200 \ x\ 6000}{4000} = 1800\Omega$

From graph 1.8kΩ corresponds to 0.48 W m^{-2}

SQA H 2008 Q26 (a)

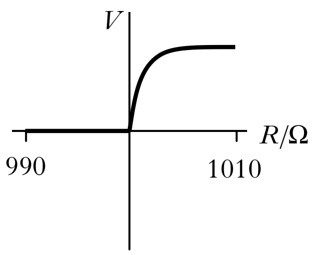
Revision – Wheatstone Bridge

Example 14
In the following Wheatstone bridge circuit, the reading on the voltmeter is zero when the resistance of R is set at 1kΩ.

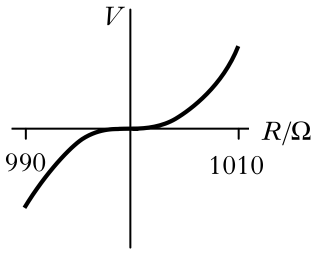


Which of the following is the graph of the voltmeter reading V against the resistance R?

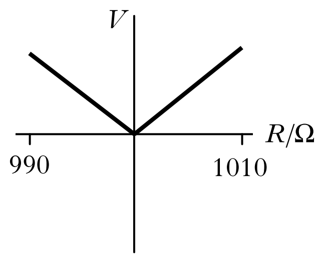
A



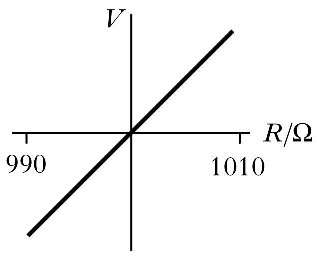
B



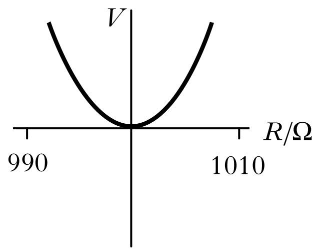
C



D



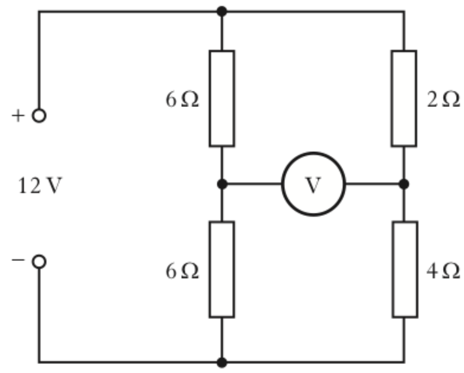
E



D

SQA H 2010 Q10

Example 15



Calculate the reading on the voltmeter.

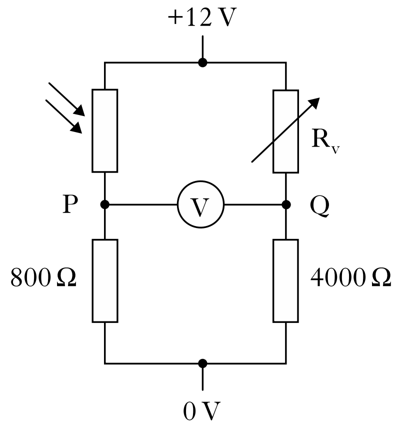
Voltage at left hand side = 6V
Voltage at right hand side = 8V

Reading on voltmeter = 8-6
= 2V

Example 16

The headlights on a truck are switched on automatically when a light sensor detects the light level falling below a certain value.

The light sensor consists of an LDR connected in a Wheatstone bridge as shown.



The variable resistor, R_v, is set at 6000Ω.

a) Calculate the resistance of the LDR when the bridge is balanced.

b) As the light level decreases the resistance of the LDR increases. Calculate the reading on the voltmeter when the resistance of the LDR is 1600Ω.

a) $\frac{R_1}{R_2} = \frac{R_3}{R_4}$ ➔ $\frac{R_{LDR}}{800} = \frac{6000}{4000}$ ➔ $R_{th} = \frac{6000 \ x \ 800}{4000}$ = 1200Ω

b) Voltage at P when the resistance of the LDR is 1600Ω

$V_P = \frac{V_S}{R_1+R_2} \times R_1 = \frac{12}{1600+800} \times 800 = 4V$

$V_Q = \frac{V_S}{R_1+R_2} \times R_2 = \frac{12}{6000+4000} \times 4000 = 4.8V$

Reading on voltmeter = $V_Q - V_P$ = 4.8 – 4 = 0.8V

SQA H 2010 Q25

Learning Outcomes – Electrical Sources and Internal Resistance

This builds on information from

At the end of this section you should be able to

- state that the electromotive force (e.m.f.) of a source is the electrical potential energy supplied to each coulomb of charge which passes through the source.
- state that an electrical source is equivalent to a source of e.m.f. with a resistor in series, the internal resistance.
- Describe what is meant by the terms – ideal supply, short circuit and open circuit.
- describe the principles of a method for measuring the e.m.f. and internal resistance of a source.
- explain why the e.m.f. of a source equals the open circuit p.d. across the terminals of a source.
- explain how the conservation of energy leads to the sum of the e.m.f.'s round a closed circuit being equal to the sum of the p.d.'s round the circuit.
- use the following terms correctly: terminal p.d., load resistor, lost volts, short circuit current.
- Carry out calculations to find e.m.f. internal resistance, load resistance and current
- Use graphical analysis to determine internal resistance and e.m.f.

Electromotive Force

The electromotive force (e.m.f.). is

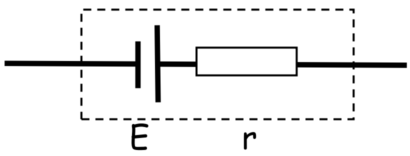
- the electrical potential energy supplied to each coulomb of charge that passes through a cell.
- Is the voltage across the terminals of a cell when no current is flowing i.e. an open circuit
- Is the maximum voltage across a cell when no current is flowing.

Example 17
The e.m.f. of a battery is

A the total energy supplied by the battery
B the voltage lost due to the internal resistance of the battery
C the total charge which passes through the battery
D the number of coulombs of charge passing through the battery per second.
E the energy supplied to each coulomb of charge passing through the battery

An ideal power supply would be able to supply a constant voltage and any current we wish provided we connect the correct resistance. We know power supplies are not ideal because if we add lamps in parallel they start to get dimmer if more are added.

Charges passing through a cell meet resistance. A cell therefore has internal resistance. This is shown as



The potential difference (p.d.) measured across the cell is the e.m.f.

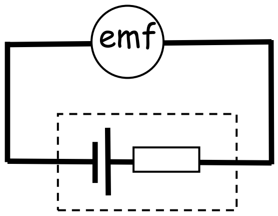
The p.d. measured across the internal resistance (r) is called the 'lost volts'. [They aren't really lost – just not available for use in the circuit]

The terminal potential difference (t.p.d.) is the potential difference measured across the terminals of the cell.

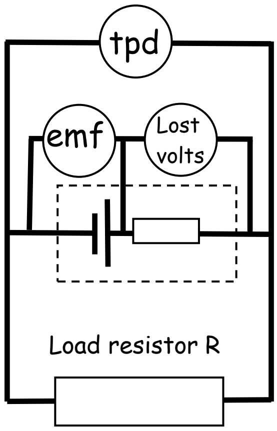
NOTE

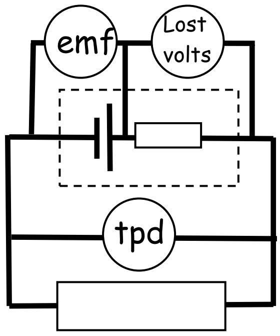
There are only lost volts when current flows in a circuit.
No current = no lost volts
No current – the p.d. across the terminals of the cell is the emf

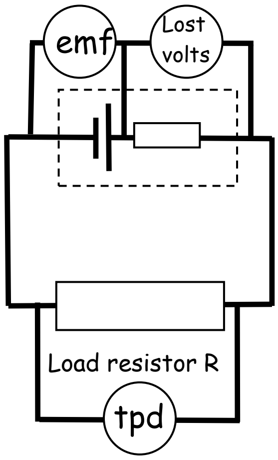
Electromotive Force and Internal resistance



There is no load connected to the cell so no current flows. The voltmeter measures the e.m.f.







These three circuits look slightly different, but they all measure the same values. The voltmeter measuring the t.p.d. is shown connected in a slightly different position each time.

The circuit shows that

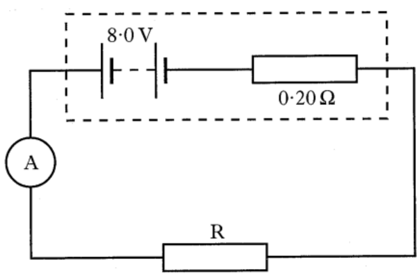
e.mf. = lost volt + t.p.d.

$E \quad = \quad Ir \quad + \quad IR \quad = I\,(r + R)$

Where E = e.m.f. (V)
I = current (A)
R = load resistance (Ω)
r = internal resistance (Ω)

Also lost volts = Ir

Example 18
In the following circuit, the battery has an e.m.f. of 8.0V and an internal resistance of 0.20Ω. The reading on the ammeter is 4.0A
Calculate the resistance of R.



$E \quad = Ir + IR$
$8.0 = (4 \times 0.20) + 4R$
$8.0 - 0.8 = 4R$
$R = 7.2/4 = 1.8\ \Omega$

SQA H 2003 Q 9 adapted

Electromotive Force and Internal resistance

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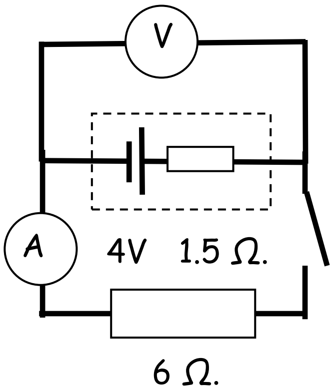
Example 19

A 6 Ω resistor is connected to a cell of e.m.f. 4.0V and internal resistance 1.5 Ω.



Calculate

a) The reading on the voltmeter when the switch is open
b) Current flowing when the switch is closed.
c) Reading on voltmeter when switch is closed
d) The lost volts.

a) V = 4V (as V = e.m.f. when no current flows)

b) E = Ir + IR = I (r +R)

4 = I (1.5 + 6)

4 = 7.5 I

I = 0.53 A

c) t.p.d. = IR

= 0.53 x 6

= 3.2V

d) Lost volts = Ir OR lost volts = 4 -3.2

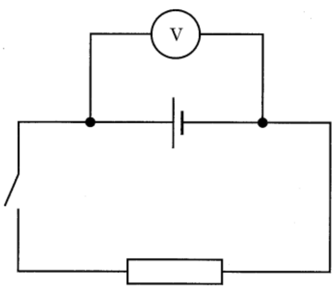
= 0.3 x 1.5 = 0.8V

= 0.8V

AHS notes

Example 20

A student sets up the following circuit



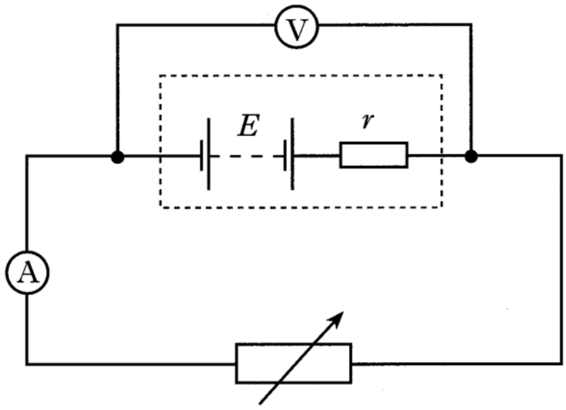
When the switch is open , the student notes that the reading on the voltmeter is 1.5V. The switch is then closed and the reading falls to 1.3V

The decrease of 0.2V is referred to as the

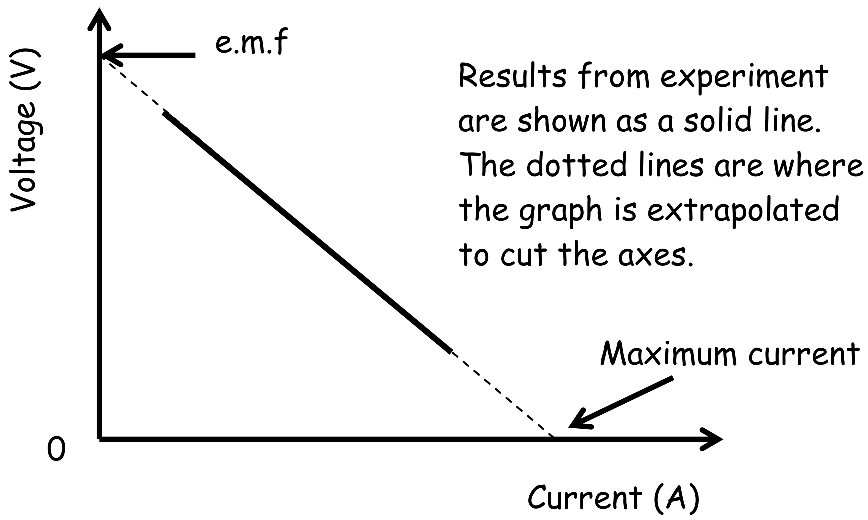
A e.m.f.
B lost volts
C peak voltage
D r.m.s. voltage
E terminal potential difference

E.m,f. and internal resistance from a graph

The circuit below is set up and readings of current and voltage are taken as the load resistor is varied from 0 to its maximum value.



The results are plotted on a graph of voltage against current.



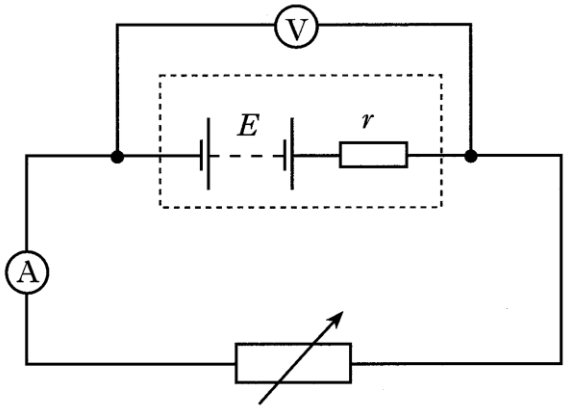
E = Ir + IR
E = Ir + V
V = -rI + E

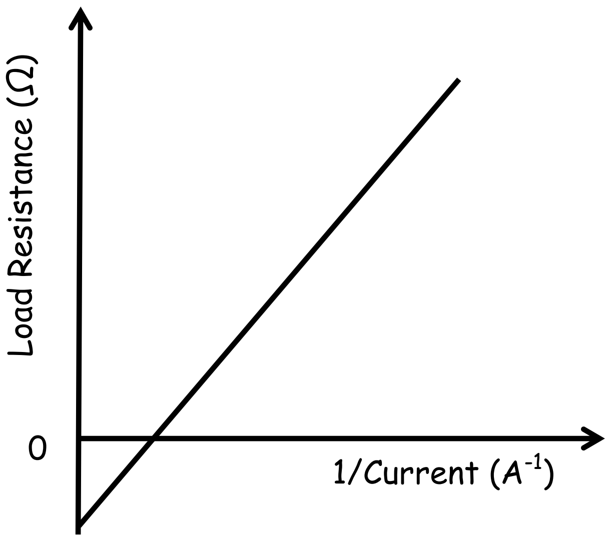
this is in the same format as y = mx +c
y intercept = E = voltage when no current flows.
Gradient = -r

The maximum current is also known as the short circuit current because it is the current when the load is zero, which is when there is a short circuit across the terminals.
This is dangerous because a very high current can be created, which could cause overheating.

E.m,f. and internal resistance from a graph

The circuit below is set up and the load resistor is varied from 0 to its maximum value. As the external resistance is changed the current in the circuit changes. A graph of load resistance against 1/current is plotted.





$E = Ir + IR$

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

$R = (E \times \frac{1}{I}) - r$

this is in the same format as $y = mx + c$

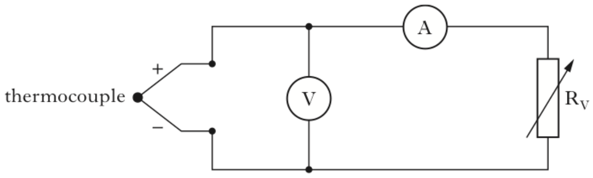
Gradient of the line = E (e.m.f.)
Y-intercept = -r (internal resistance)

E.m,f. and internal resistance from a graph

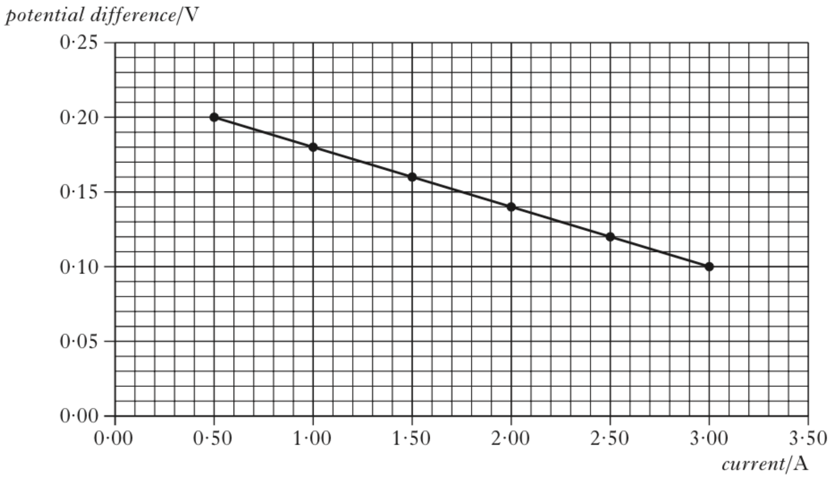
Example 21

A thermocouple is a device that produces e.m.f. when heated.

(a) A technician uses the circuit shown to investigate the operation of a thermocouple when heated in a flame.



Readings of current and potential difference (p.d.) are recorded for different settings of the variable resistor R_V. The graph of p.d. against current is shown.



Use information from the graph to find:

(i) the e.m.f. produced by the thermocouple

(ii) the internal resistance of the thermocouple

a) (i) Extrapolate the line back until it cuts the y-axis. E.m.f. = 0.22V

(ii) E = V + Ir => 0.22 = 0.10 + 3r => r = 0.04Ω

OR

use r = -gradient of graph

$$r = -\left(\frac{V_2 - V_1}{I_2 - I_1}\right) = -\left(\frac{0.1 - 0.2}{3.00 - 0.5}\right) = 0.04\Omega$$

OR

V = I (R+r)

0.2 = 0.5 (0.4 +r)

r = 0.04 Ω

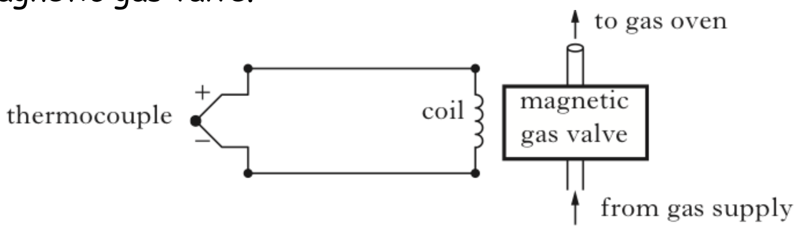
OR

Use short circuit current

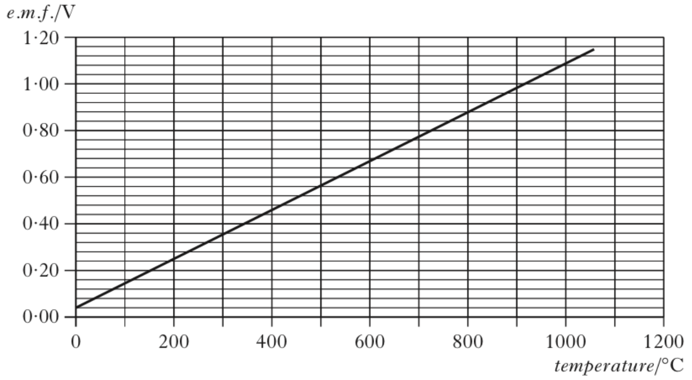
$$r = \frac{e.m.f.}{I_{short\ circuit}} = \frac{0.22}{5.5} = 0.04\Omega$$

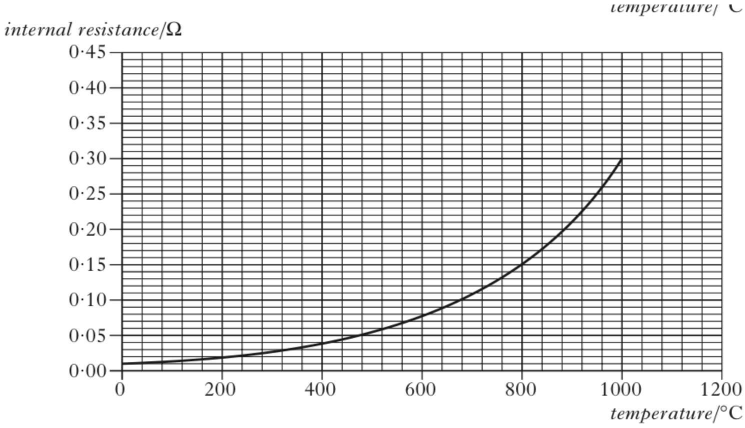
E.m,f. and internal resistance from a graph

(b) A **different** thermocouple is to be used as part of a safety device in a gas oven. The safety device turns off the gas supply to the oven if the flame goes out. The thermocouple is connected to a coil of resistance 0.12 Ω which operates a magnetic gas valve.



When the current in the coil is less than 2.5A, the gas valve is closed.
The temperature of the flame in the gas oven is 800°C.
The manufacturer's data for this thermocouple is shown in the two graphs.





Is this thermocouple suitable as a source of e.m.f. for the gas valve to be open at a temperature of 800°C.
You must justify your answer.
Get values for E and r from graphs (E = 0.88V, r = 0.15 Ω)
E = I(R+r) => 0.88 = I (0.12 +0.15) => I = 3.26A
Yes /valve open

SQA H 2013 (revised) Q 30

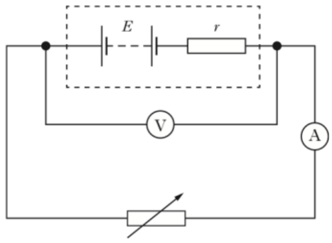
E.m,f. and internal resistance from a graph

Example 22

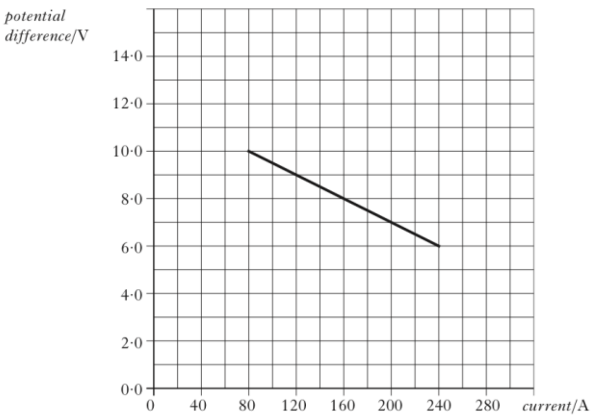
A technician is testing a new design of car battery.

The battery has an e.m.f. E and internal resistance r.

b) In one test, the technician uses this battery in the following circuit



Readings from the voltmeter and ammeter are used to plot the following graph



(i) Use information from the graph to determine the e.m.f. of the car battery.

(ii) Calculate the internal resistance of the car battery

(iii) The technician accidentally drops a metal spanner across the terminals of the battery. This causes a short circuit. Calculate the short circuit current.

(i) Extrapolating backwards – e.m.f. = 12.0V

(ii) Internal resistance = -gradient of graph

$$r = -\left(\frac{y_2 - y_1}{x_2 - x_1}\right) = -\left(\frac{6 - 10}{240 - 80}\right) = -\frac{-4}{160} = 0.025\Omega$$

OR E = I(R+r)

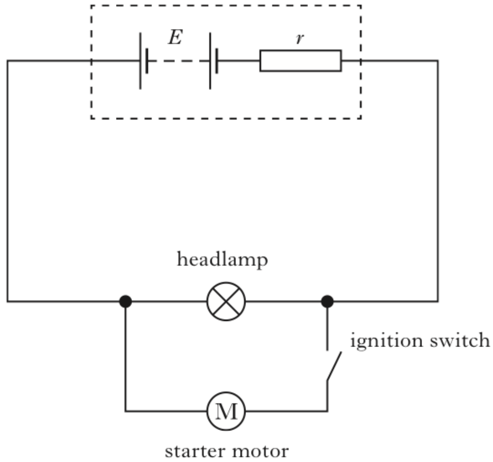
12 = 80 (0.125 + r)

r = 0.025 Ω

OR $r = \dfrac{\text{e.m.f.}}{I_{\text{short circuit}}} = \dfrac{12}{480} = 0.025\ \Omega$

(iii) Maximum current I = E/r = 12/0.025 = 480A

b) In a second test, the technician connects the battery to a headlamp in parallel with a starter motor as shown.



The technician notices that the headlamp becomes dimmer when the ignition switch is closed and the starter motor operates.
Explain why this happens.

Total resistance in circuit decreases
Current increases
Larger value of lost volts
So less voltage across headlights
(therefore headlight dimmer)

SQA 2014 H(revised) Q30

Example 23
A car battery has an e.m.f. of 12V and an internal resistance of 0.050 Ω.
(i) Calculate the short circuit current for this battery

$$I_{max} = \frac{12}{0.050} = 240A$$

(ii) The battery is now connected in series with a lamp. The resistance of the lamp is 2.5 Ω. Calculate the power dissipated in the lamp.

$I = \frac{E}{R+r} = \frac{12}{2.5+0.050} = 4.7A$ lost volts = Ir = 4.7 x 0.05 = 0.24V

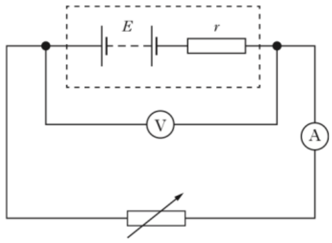
Voltage across lamp = tpd = E – lost volts = 12 – 0.24 = 11.76V

$$P = \frac{V^2}{R} = \frac{11.76^2}{2.5} = 55.3W$$

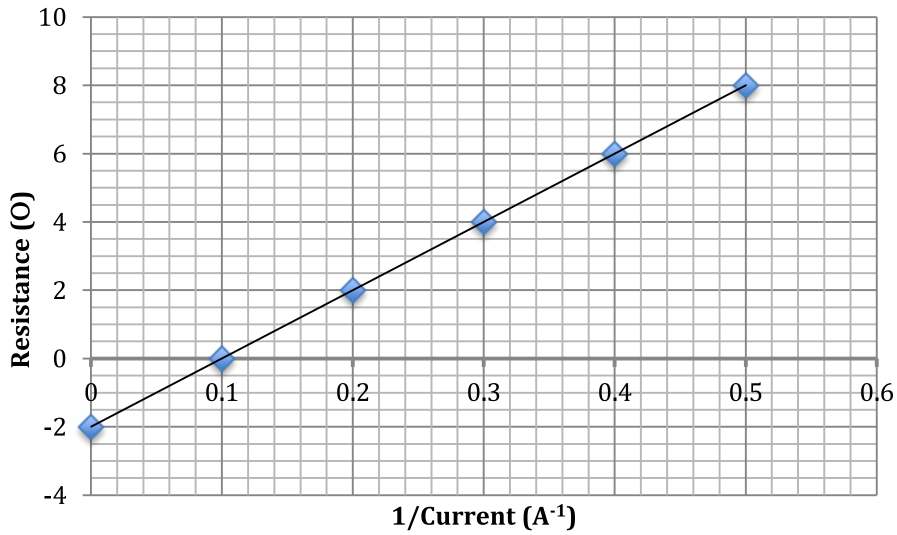
E.m,f. and internal resistance from a graph

Example 24

A student uses the circuit shown below to measure the internal resistance r and e.m.f E of a battery.



The results are plotted in the graph shown.



a) Explain why plotting an R against 1/I graph allows E and r to be determined.
b) Determine the internal resistance r
c) Determine the e.m.f. E.

a) $E = Ir + IR \Rightarrow \frac{E}{I} = R + r \Rightarrow R = \left(E \times \frac{1}{I}\right) - r$

this is in the same format as y = mx +c

E corresponds to gradient of graph

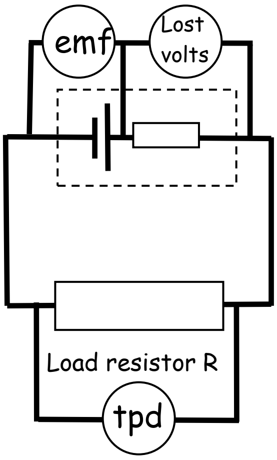
-r corresponds to intercept

b) r = 2 Ω

c) gradient of line = E = $\left(\frac{y_2-y_1}{x_2-x_1}\right)$ = - $\left(\frac{8-(-2)}{0.5-0}\right)$ = $\frac{10}{0.5}$ =20V

AHS questions

Conservation of energy



The total resistance in this circuit is given by $R_t = R + r$

From Ohm's Law $I = \frac{V}{R}$ But $I = \frac{Q}{t}$

If the current in the circuit is one ampere, one coulomb of charge is passing each point in the circuit every second.

Since $E_w = QV$, $V = \frac{E_W}{Q}$, so each coulomb of charge gains one joule of energy per volt as it passes through the cell.

The energy gained from the cell is lost as the charge passes through each resistor.

e.m.f. = $IR_{internal} + IR_{load}$ = (p.d.)$R_{internal}$ + (p.d.)R_{load}

Conservation of energy shows that the sum of the e.m.f.'s round a closed circuit is equal to the sum of the p.d.'s round the circuit.

Load matching

The maximum power is transferred when the load resistance (R) equals the internal resistance (r). This can be shown in a proof, but this is not necessary for this course.

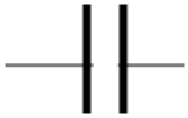
Learning Outcomes – Capacitors

This builds on information from

At the end of this section you should be able to

- state that the charge, Q, stored on two parallel conducting plates is directly proportional to the p.d. between the plates.
- describe the principles of a method to show that the p.d. across a capacitor is directly proportional to the charge on the plates.
- state that capacitance is the ratio of charge to p.d.
- state that the unit of capacitance is the farad and that one farad is one coulomb per volt.
- carry out calculations using $C = Q/V$
- explain why work must be done to charge a capacitor.
- Sketch a graph of charge against potential difference.
- state that work done charging a capacitor equals the area under the graph of charge vs. p.d.
- state that the energy stored in a capacitor is given by $E = \frac{1}{2}$ (charge × p.d.) and equivalent expressions.
- carry out calculations using $E = \frac{1}{2} QV$ and equivalent expressions.
- draw qualitative graphs of current against time and of voltage against time for the charge and discharge of a capacitor in a d.c. circuit containing a resistor and capacitor in series.
- Show the effect on charge and discharge curves in RC circuits when capacitance and resistance are altered.
- carry out calculations involving voltage and current in RC circuits.
- state the relationship between current and frequency in a capacitive circuit.
- describe a method to show how the current varies with frequency in a capacitive circuit.
- describe and explain possible functions of a capacitor: e.g. storing energy, blocking d.c. while passing a.c.

Capacitors – Background Information



Circuit symbol for a capacitor

A capacitor consists of two metal plates separated by a gap. The gap can be an air gap but it can also be filled by another insulating material (called the dielectric).

Capacitance is measured in Farads (F). One Farad is a very large value, so more common values are μF, nF or pF. (10^{-6}, 10^{-9} and 10^{-12} respectively)

Capacitors can be used to store charge, to create time delays, to block d.c., to create tuned circuits and to help improve the output of circuits converting a.c. to d.c.

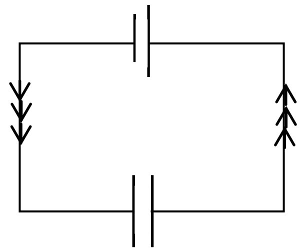
Remember to use the correct terminology.

A greater resistance or greater capacitance is correct.

A bigger resistor or bigger capacitor IS NOT CORRECT!!!

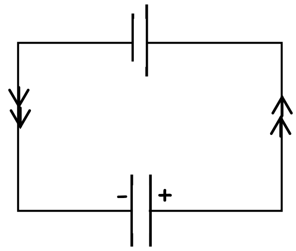
Capacitors – Background Information

Big Current



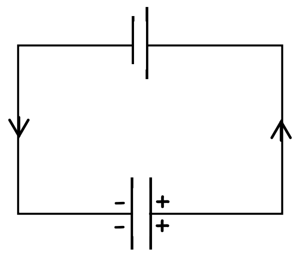
No charge on the capacitor so the charge builds up quickly.

Medium Current



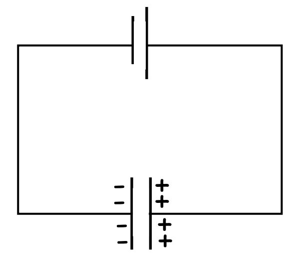
A small charge on the capacitor so the charge builds up more slowly.

Small Current

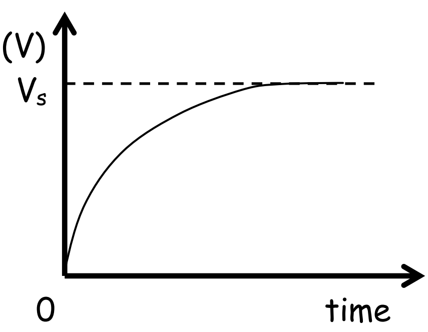


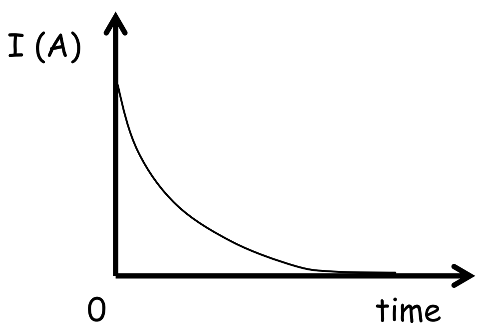
The capacitor is nearly fully charged so the current is small.

No Current



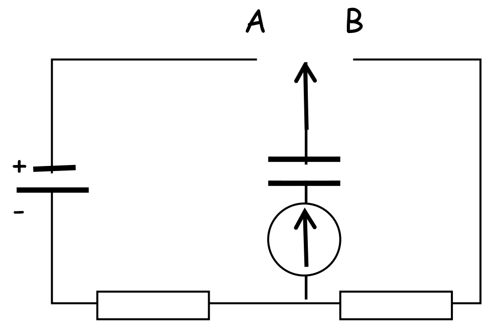
The capacitor is fully charged so there is no current.



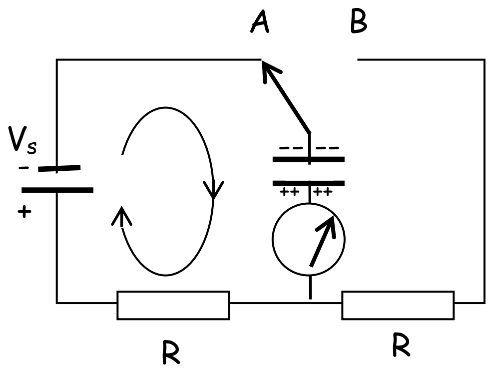


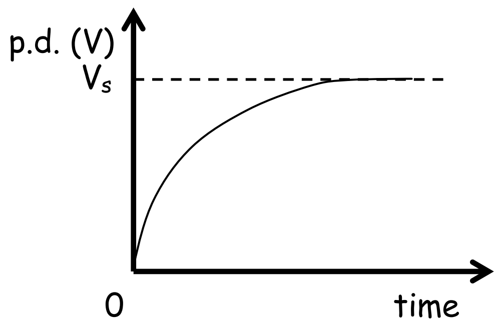
Capacitors – Charging a capacitor

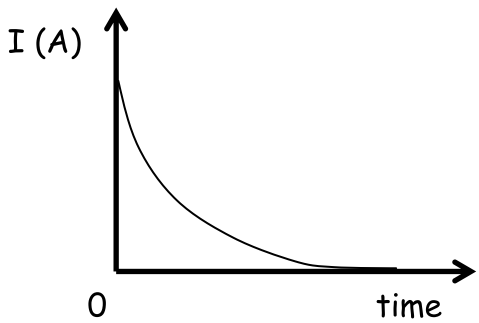
Capacitor initially discharged.



Switch moved to A. Capacitor starts to charge up.

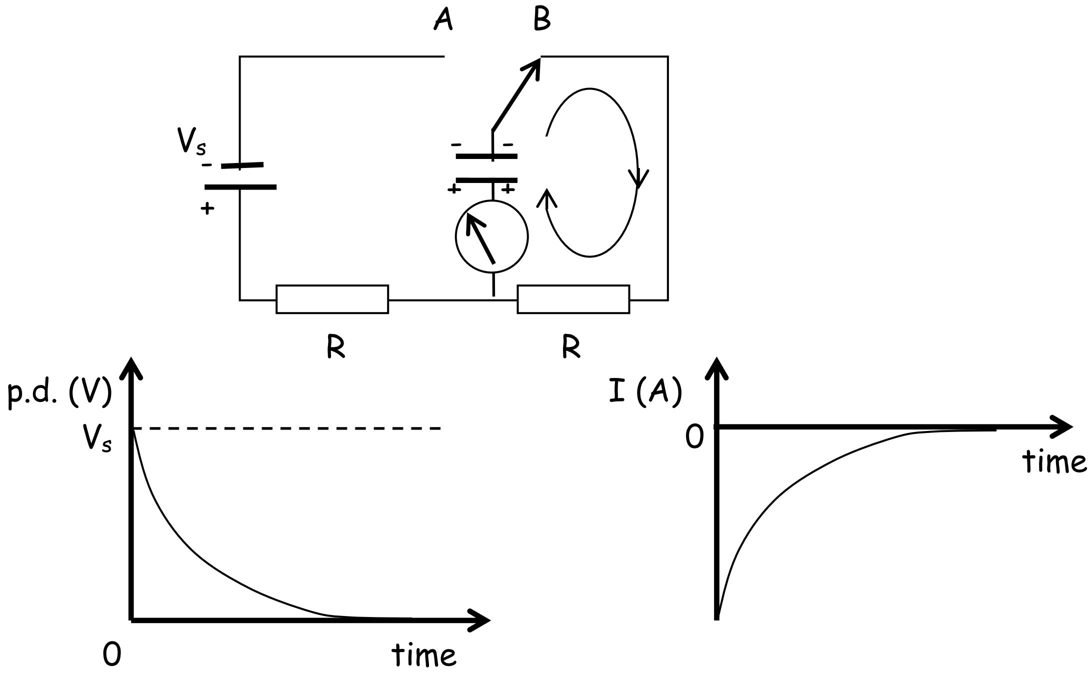






When the switch moves to position A current begins to flow in the circuit.
The initial current can be calculated using $\frac{V_s}{R}$.
As charge builds up on the capacitor the current flowing from the cell starts to decrease.
When the capacitor is fully charged the potential difference across the cell equals the potential difference across the supply.
When the capacitor is fully charged no more current can flow.
The time taken for this to happen depends on the capacitance and resistance in the circuit.

Capacitors – Discharging a capacitor

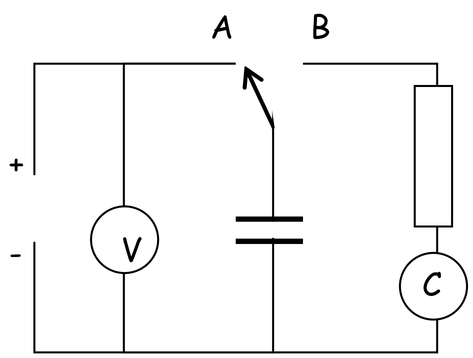


After the capacitor is fully charged the switch is moved to position B. There is no cell in this circuit. The voltage at the start is the potential difference across the capacitor caused by the charge stored on the plates.
As the current flows in the circuit the potential difference across the capacitor decreases until there is no charge left on the plates. The voltage is then zero.
The current starts off at a maximum value determined by the potential difference across the capacitor and the resistance in the circuit.
Current flows from negative to positive – this means that as it flows through the centre zero meter the current is in the opposite direction to that observed during charging.
As the capacitor discharges the current decreases to zero.

SUMMARY

- The discharging current is in the opposite direction to the charging current
- Both charging and discharging currents end at 0A.
- The capacitor always charges to the supply voltage and discharges to 0V.
- If the capacitance or resistance is increased it will take longer to charge.

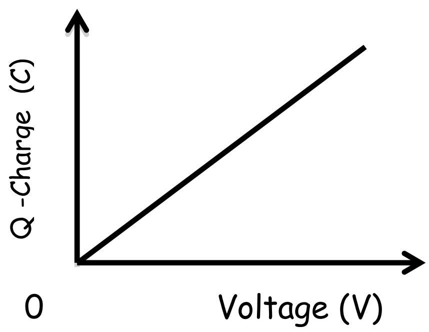
Capacitors – Charge and potential difference



Switch to A - The capacitor fully charges and the voltage is taken from the reading on the voltmeter.

Switch to B - The capacitor discharges and the coulombmeter measures the charge that was stored on the capacitor.

The experiment is repeated for many different voltages and a graph of charge against voltage is drawn.



The graph shows that

$Q \propto V$

$Q = kV$

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

The constant is known as capacitance, so

$C = \frac{Q}{V}$ or $Q = VC$

Definition of capacitance

Since $C = \frac{Q}{V}$ one Farad = one Coulomb per Volt

This means that a 600μF capacitor can store 600μC of charge per volt.

Example 25

A 620 μF capacitor is connected to a 6V power supply. What will be the charge on the plates when the capacitor is fully charged?

$C = 620\ \mu F$ $Q = VC = 6 \times 620 \times 10^{-6} = 3.72 \times 10^{-3} C$

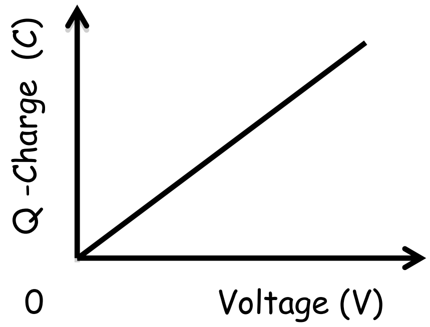
$V = 6V$

$Q = ?$

AHS notes

Energy stored in a capacitor

If we plot a graph of charge against voltage we can calculate the energy stored in a capacitor.



$E = \frac{1}{2} QV = \frac{1}{2} CV^2 = \frac{1}{2} \frac{Q^2}{C}$

Since $E_w = QV$

Energy = Area under graph

$E = \frac{1}{2} QV$

But $Q = VC$

$E = \frac{1}{2} V \times VC$

$E = \frac{1}{2} CV^2$

But $V = \frac{Q}{C}$

$E = \frac{1}{2} Q \frac{Q}{C}$

$E = \frac{1}{2} \frac{Q^2}{C}$

Example 26

A capacitor of 500 μF stores 600mJ of energy.

(a) Calculate the p.d. across the capacitor

(b) How much charge is stored in the capacitor?

(a) $C = 500\mu F$, $E = 600mJ$, $V = ?$

$E = \frac{1}{2} CV^2$

$600 \times 10^{-3} = \frac{1}{2} \times 500 \times 10^{-6} \times V^2$

$V^2 = 2400$

$V = 49V$

(b) $Q = VC$

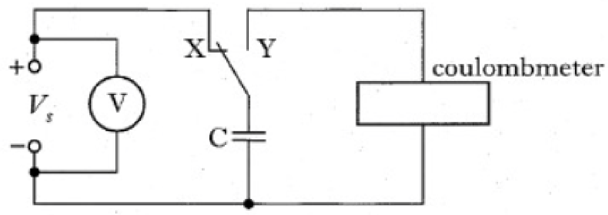
$= 49 \times 500 \times 10^{-6}$

$= 0.0245C$

AHS notes

Energy stored in a capacitor

Example 27
In an experiment to measure the capacitance of a capacitor, a student sets up the following circuit.



When the switch is in position X, the capacitor charges up to the supply voltage V_S. When the switch is in position Y, the coulombmeter indicates the charge stored by the capacitor.

The student records the following measurements and uncertainties.

Reading on voltmeter = (2.56 ± 0.01) V
Reading on coulombmeter = (32 ± 1) μC

Calculate the value of the capacitance and the percentage uncertainty in this value. You must give the answer in the form
Value ± percentage uncertainty

$$C = \frac{Q}{V} = \frac{32 \times 10^{-6}}{2.56} = 1.25 \times 10^{-5}\ \text{F}$$

% uncertainty in voltage = $\frac{0.01}{2.56}$ x 100 = 0.4 %

% uncertainty in charge = $\frac{1}{32}$ x 100 = 3.125%

Use % uncertainty in charge since it is the largest %.

$C = 1.25 \times 10^{-5} \pm 3.1\ \%\text{F}$

SQA H 2000 Q24 (a)

Example 28
A 2200 μF capacitor is connected across a 12 V supply. What is the maximum energy stored in the capacitor?

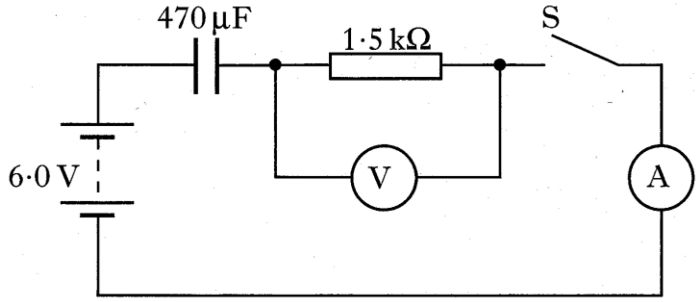
$$E = \tfrac{1}{2} CV^2 = \tfrac{1}{2} \times 2200 \times 10^{-6} \times 12^2 = 0.16\ \text{J}$$

SQA H 2000 Q24 (b) (i) (adapted)

Charging and discharging a capacitor

Example 29

The following diagram shows a circuit that is used to investigate the charging of a capacitor.



The capacitor is initially uncharged.

The capacitor has a capacitance of 470 μF and the resistor has a resistance of 1.5 kΩ.

The battery has an e.m.f. of 6.0V and negligible internal resistance.

(i) Switch S is now cloased. What is the initial current in the circuit?

(ii) How much energy is stored in the capacitor when it is fully charged?

(iii) What change could be made to this circuit to ensure that the **same** capacitor stores **more** energy?

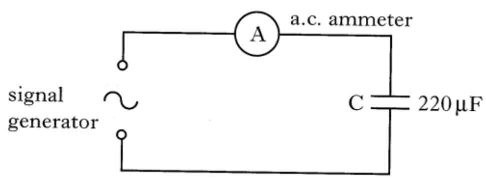
(i) $I = \frac{V}{R} = \frac{6.0}{1.5 \times 10^{-3}} = 4 \times 10^{-3}$ A

(ii) $E = \frac{1}{2}CV^2 = 1/2 \times 470 \times 10^{-6} \times 6^2 = 8.46 \times 10^{-3}$ J

(iii) Increase the supply voltage OR use a battery of higher e.m.f.

SQA H 2001 Q 25

Example 30



The signal generator is adjusted to give a peak output voltage of 12V at a frequency of 300Hz. The internal resistance of the signal generator and the resistance of the a.c. ammeter are negligible. Calculate the **maximum** energy stored by the capacitor during one cycle of the supply voltage.

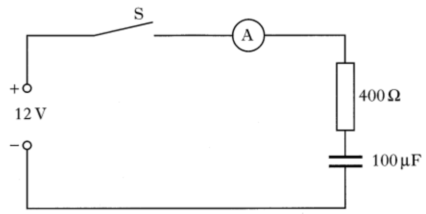
$E = \frac{1}{2}CV^2 = \frac{1}{2} \times 220 \times 10^{-6} \times 12^2 = 0.016$ J

SQA H 2003 Q 25 (b)(ii)

Charging and discharging a capacitor

Example 31

In an experiment, the circuit shown is used to investigate the charging of a capacitor.



The power supply has an e.m.f. of 12V and negligible internal resistance. The capacitor is initially uncharged.
Switch S is closed and the current measured during charging. The graph of charging current against time is shown in figure 1.

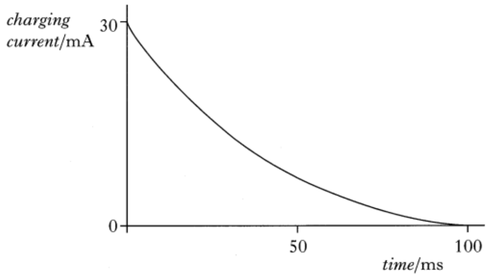


figure 1

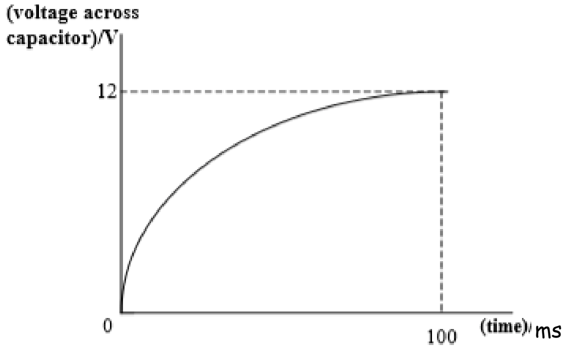
(a) Sketch a graph of the voltage across the capacitor against time until the capacitor is fully charged. Numerical values are required on both axes.

(b) (i) Calculate the voltage across the capacitor when the charging current is 20mA?

(ii) How much energy is stored in the capacitor when the charging current is 20mA?

(c) The capacitor has a maximum working voltage of 12 V. Suggest **one** change to this current which would allow an initial charging current of greater than 30mA.

(a)



Energy stored in a capacitor

(d) The 100μF capacitor is now replaced by an uncharged capacitor of unknown capacitance and the experiment is repeated. The graph of charging current against time for this capacitance is shown in figure 2.

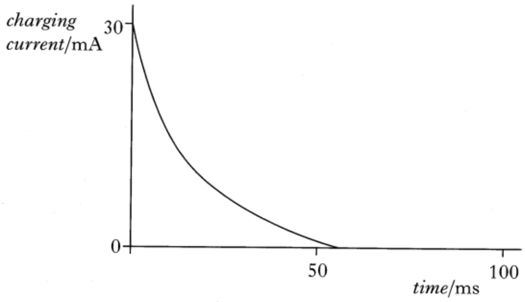


figure 2

By comparing figure 2 with figure 1, determine whether the capacitance of this capacitor is greater than, equal to or less than 100μF. You must justify your answer.

b) (i) $V_R = IR = 20 \times 10^{-3} \times 400 = 8V$

$V_c = 12 - 8 = 4V$

b) (ii) $E = \frac{1}{2} CV^2 = \frac{1}{2} \times 100 \times 10^{-6} \times 4^2 = 8 \times 10^{-4} J$

OR

$Q = CV = 100 \times 10^{-6} \times 4 = 4 \times 10^{-4} (C)$

$E = \frac{1}{2} QV = \frac{1}{2} \times 4 \times 10^{-4} \times 4 = 8 \times 10^{-4} J$

C) Resistor value less than 400Ω

OR

Use larger voltage supply but do not charge above 12V

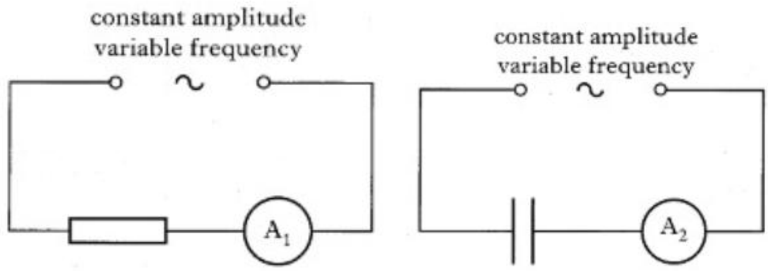
OR Remove resistance

d) charging current on for shorter time (so smaller charge required to reach 12V) (so value of C) less/smaller than 100μF.

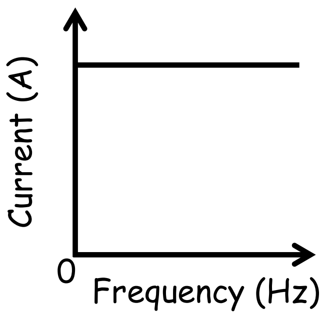
OR smaller area under graph (so less charge stored for same V) So smaller value of C.

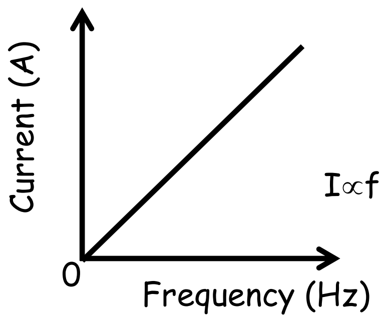
SQA H 2006 Q25

Current and Frequency in a Resistive Circuit



In both circuits the frequency of the supply is altered while the voltage is kept constant. Readings of the current are taken at regular intervals. The results are plotted on a graph of current against frequency.



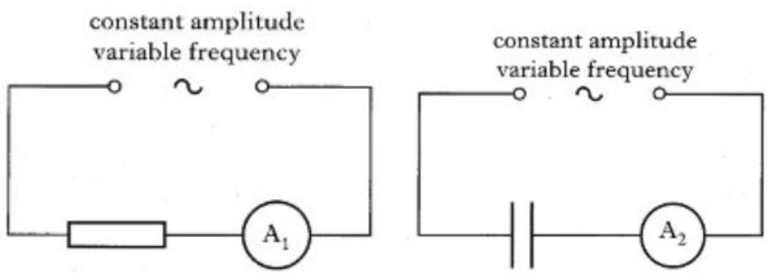


The current through a resistor is unaffected by changes in frequency.

The current through a capacitor is directly proportional to changes in frequency.

At high frequencies the capacitor never has time to become fully charged before the current changes direction, so there is always current flowing.

Example 32
The circuits below have identical a.c. supplies which are set a frequency of 200Hz. A current is registered on each of the ammeters A_1 and A_2.

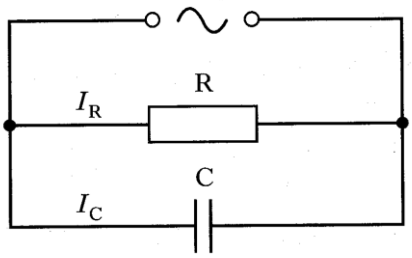


The frequency of each a.c. supply is now increased to 500Hz.
What happens to the readings on ammeters A_1 and A_2?

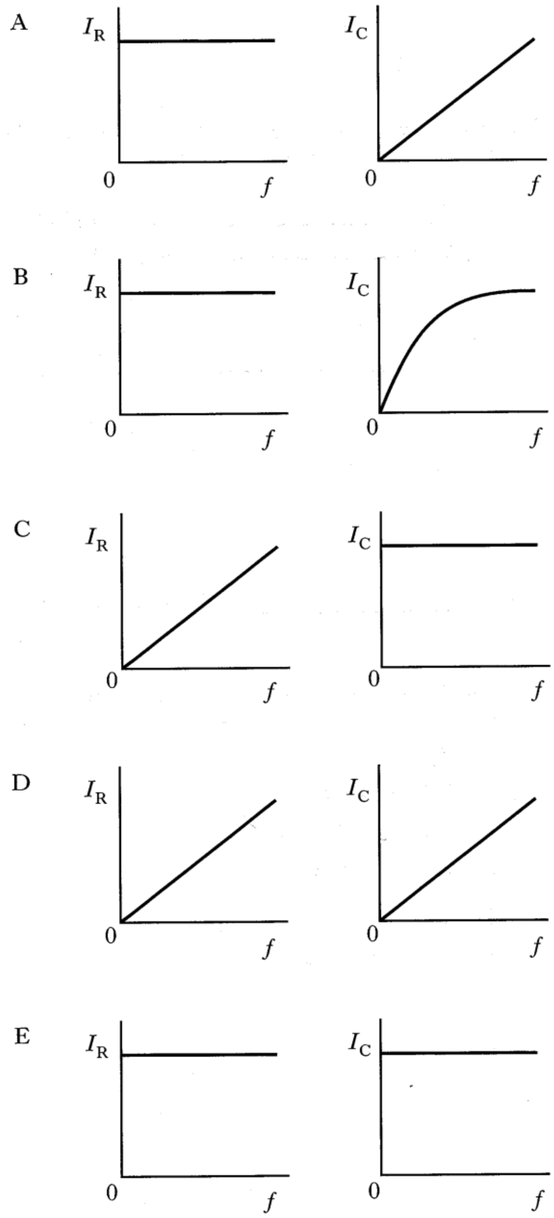
A_1 – constant $\quad$ A_2 - increases $\quad$ SQA H 2000 Q 10

Uses of Capacitors

Example 33
The following circuit shows a constant voltage a.c. supply connected to a resistor and capacitor in parallel.



Which pair of graphs shows how the r.m.s. currents I_R and I_C vary as the frequency f of the supply is increased?



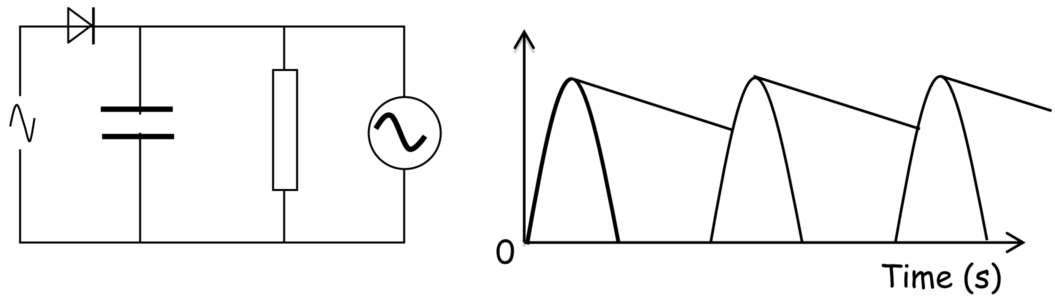
Uses of Capacitors

Storing Energy
A capacitor stores the energy from a battery when it becomes charged. This energy can be released rapidly, creating a high current. This is used in camera flashes.

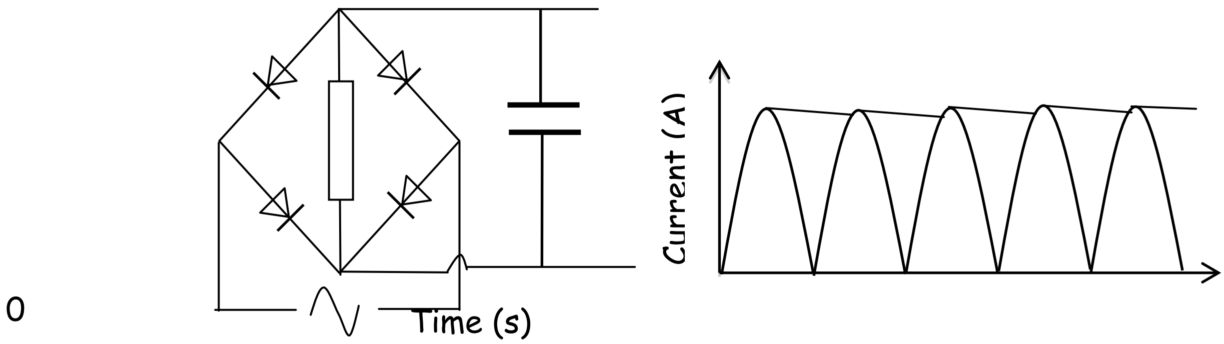
Time Delay Circuits
The capacitance of a capacitor affects the time it takes to become fully charged – the higher the capacitance the longer the time taken.
This can be used to introduce a time delay in a circuit or to produce regular pulses.

Blocking Capacitor
A capacitor will stop the flow of direct current but will let alternating current pass. This can be used to control the input signal used by an oscilloscope.

Converting Alternating Current to Direct Current
Passing alternating current through a diode removes half of the signal, but the d.c. produced is not smooth. If a capacitor is added to the circuit as shown below it helps to smooth the output signal.



Using a single diode produces a poor quality d.c. output. Adding a capacitor helps to improve it, but the signal still varies.
The full wave rectifier circuit, shown below, has four diodes connected to improve the output signal. When a capacitor is connected across the output the d.c. produced is better still.



Uses of Capacitors

Example 34

Which of the following statements about capacitors is/are true?

I Capacitors are used to block d.c. signals

II Capacitors are used to block a.c. signals

III Capacitors can store energy

IV Capacitors can store electric charge.

A I only

B I and III only

C II and III only

D I, III and IV only

E III and IV only

Example 35

Recent innovations to capacitor technology have led to the development of 'ultracapacitors'. Ultracapacitors of a similar size to standard AA rechargeable cells are now available with ratings of around 100F with a maximum working voltage at 2.7V

By comparison, AA rechargeable cells operate at 1.5V and can store up to 3400mAh of charge.

(*charge* in mA h = *current* in mA x *time* in hours)

Use your knowledge of physics to compare the advantages and/or disadvantages of using ultracapacitors and rechargeable cells.

Ultracapacitors

- Can charge and discharge much faster than batteries
- Can do so millions of times without degrading
- Have little or no internal resistance and work close to 100% efficiency
- Are significantly lighter in weight than batteries
- Don't contain harmful chemicals or toxic metals.

They are ideally suited for applications that require high bursts of power such as

- Adjusting solar arrays on spacecraft
- Providing starting currents for trucks
- Powering kinetic energy recovery systems (KERS) in vehicles

SQA H 2014 (revised) Q31

Electricity Problem Booklet
P22 Q 1 - 17

Learning Outcomes – Conductors, Semiconductors and Insulators

This builds on information from

At the end of this section you should be able to

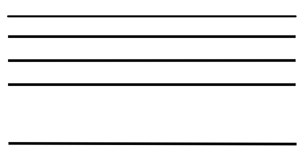
- State that solids can be categorised into conductors, semi-conductors or insulators by their ability to conduct electricity.
- Describe what is meant by the terms *conduction band* and *valance band*.
- Describe the electrical properties of conductors, insulators and semiconductors using the electron population of the conduction and valance bands and the energy difference between the conduction and valance bands.

Conductors, Semiconductors and Insulators

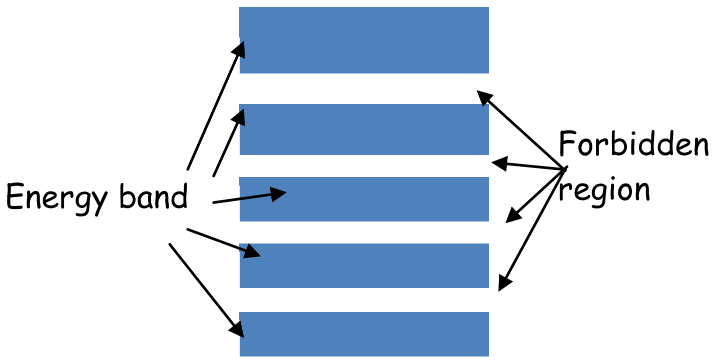
	Conductor	Semiconductor	Insulator
Definition	Materials with many free electrons, which can easily move through the material.	Materials which are insulators when pure, but will conduct when an impurity is added and/or in response to heat, light or a voltage	Materials with very few free electrons, which cannot move easily through the material
Examples	All metals, graphite, antimony, arsenic	Silicon Germanium	Plastics, glass, wood.

Band theory
Electrons in an isolated atom occupy discrete energy levels.

When arranged in the crystal lattice of a solid the electrons in adjacent atoms cannot occupy the same energy levels, so many more slightly different energy levels come into existence creating a band of permitted energy levels.



Simple representation of energy levels in an isolated atom



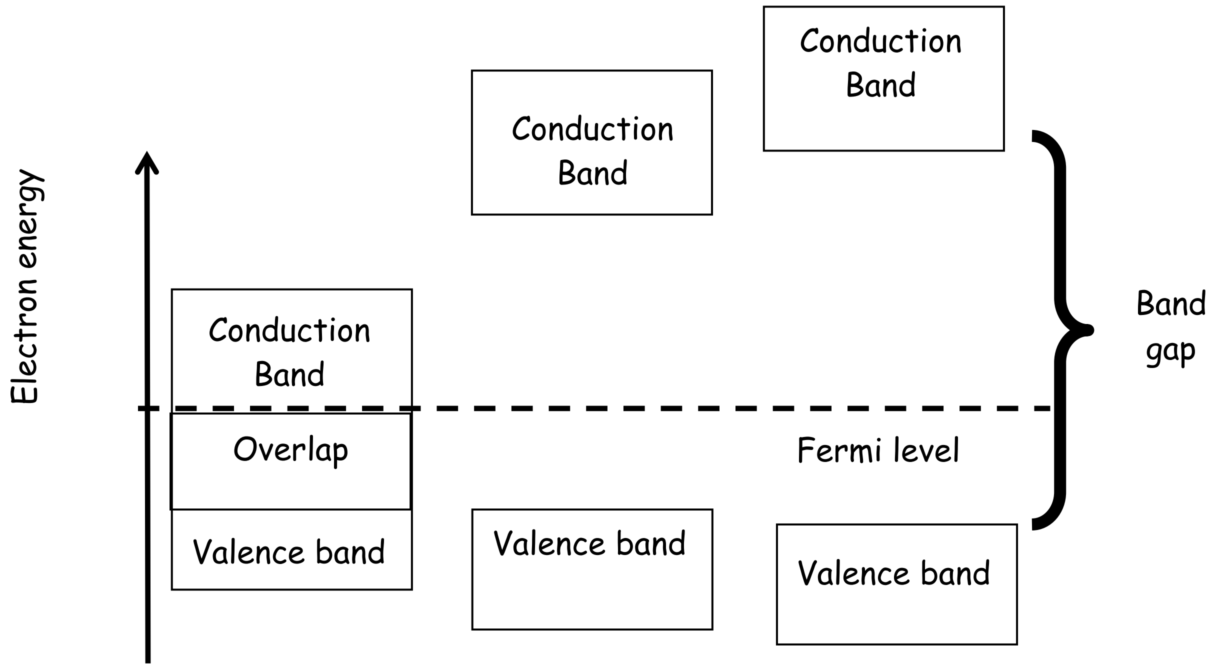
Electrons can be found in the energy bands but cannot occupy the forbidden regions.

The Fermi level is an energy level where there is an equal probability of finding an electron or not finding an electron. When temperatures approach absolute zero this level is the top of the allowed energy levels.

Conductors, Semiconductors and Insulators

The two highest energy levels are the valence band and the conduction band.

The electrons are held tightly in the valence band, but are able to move freely in the conduction band. If there are electrons in the conduction band the material will conduct. If there are no electrons in the conduction band the solid will not conduct.



	Conductor	Semiconductor	Insulator
Conduction band	Contains electrons, but not completely full. Electrons can move, allowing conduction. Overlaps with valence band.	Electrons reaching this band will conduct.	No electrons in the conduction band.
Band gap	No band gap because of overlap.	Small gap between the valence and conduction bands. At room temperature some electrons can make this move.	Gap is too large for electrons to move up to the conduction band at room temperature.
Valence band	Overlaps with conduction band.	Full of electrons	Full of electrons.

Conductors, Semiconductors and Insulators

Example 36
Fill the gaps in the following passage,

Solids can be divided into three broad categories: conductors, insulators and semiconductors.

In _*conductors*_ the conduction band is not completely full and this allows electrons to move easily.
In _*insulators*_ the valence band is full.
In *semiconductors*_ the energy gap between the valence band and the conduction band is _*small*_ allowing *some* _ conduction to take place at room temperature

SQA H 2014 (revised) Q18, 2013 (revised) Q20 [adapted]

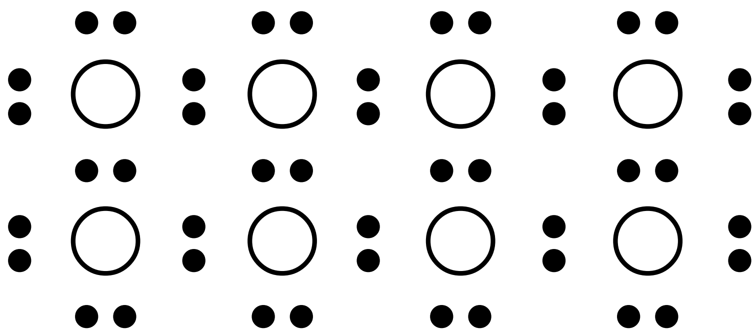
Learning Outcomes – p-n junctions

This builds on information from

At the end of this section you should be able to

- State that, during manufacture, the conductivity of semiconductors can be controlled, resulting in two types: n-type and p-type.
- Know that, when p-type and n-type materials are joined a layer is formed at the junction. The electrical properties of this layer are used in a number of devices.
- Explain the terms *forward bias* and *reverse bias.*
- Know that solar cells are p-n junctions designed so that a potential difference is produced when photons enter the layer. (This is known as the photovoltaic effect).
- Know that LEDs are forward biased p-n junction diodes that emit photons when electrons 'fall' from the conduction band into the valance band of the p-type semiconductor.

Semiconductor Structure

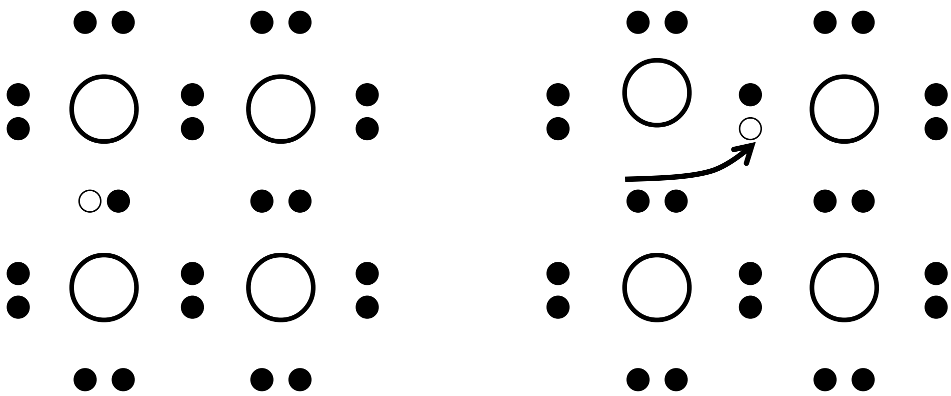


In a pure semiconductor, such as silicon or germanium, there are four outer electrons which bond covalently to the surrounding atoms. The resistance is very high because there are few free electrons available.

The available electrons are either due to imperfections or come from thermal ionisation due to heating. If the temperature increases more electrons become available and the resistance decreases. This is like a thermistor.

Holes
If an electron moves from one place to another in the crystal lattice, the space left behind is called a **positive hole**. Although it is the electron moving it gives the same impression as the positive hole moving in the opposite direction.

Hole movement

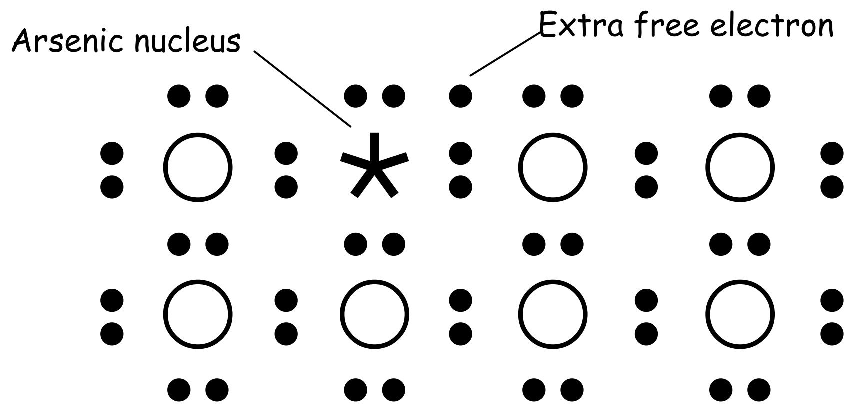


Before After

It looks like the hole has moved from left to right, what has actually happened is that an electron has moved from right to left.
In an undoped semiconductor the number of holes is equal to the number of electrons.

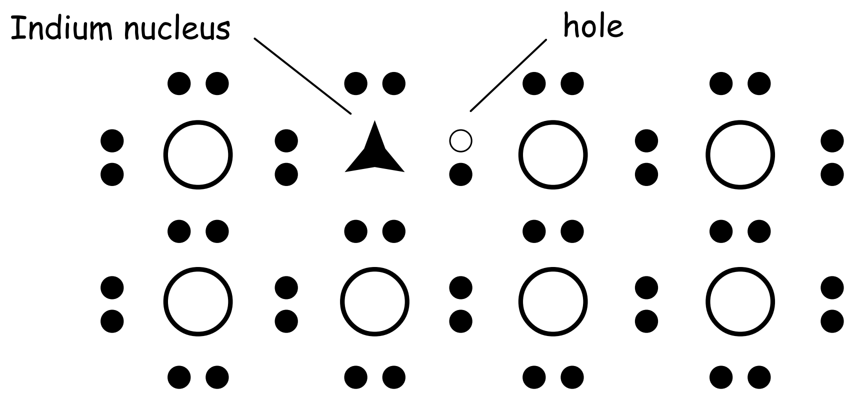
Semiconductor Doping

Doping
A semiconductor material becomes doped if a small amount of material from another element is added to the base material. If the element added, e.g. Arsenic, has 5 electrons in the outermost shell the 'extra' electron doesn't bond in the lattice and is free to move.



This is called an **n-type semiconductor** since the free charge carriers are electrons, which are negative.

If the element added, e.g. Indium, has 3 electrons in the outermost shell there is a 'missing' electron. This produces a hole, which is free to move.



This is called a **p-type semiconductor** since the free charge carriers are holes, which are positive.

Both n-type and p-type semiconductors are electrically neutral – the number of protons and number of electrons in the material are equal. Although it is only electrons which move, in an n-type semiconductor the free charge carriers are negative, in a p-type semiconductor the free charge carriers are positive.

Semiconductor Doping

Example 37

A student writes the following statements about n-type semiconductor material.

I Most charge carriers are negative
II The n-type material has a negative charge
III Impurity atoms in the material have 5 outer electrons

Which of these statements is/are true?

A I only
B II only
C III only
D I and II only
E I and III only

SQA H 2003 Q 19

Example 38

A crystal of silicon is 'doped' with arsenic. This means that a small number of the silicon atoms are replaced with arsenic atoms.

The effect of the doping on the crystal is to

A make it into a photodiode
B make it into an insulator
C increase its resistance
D decrease its resistance
E allow it to conduct in only one direction

SQA H 2012 (revised) Q20

Example 39

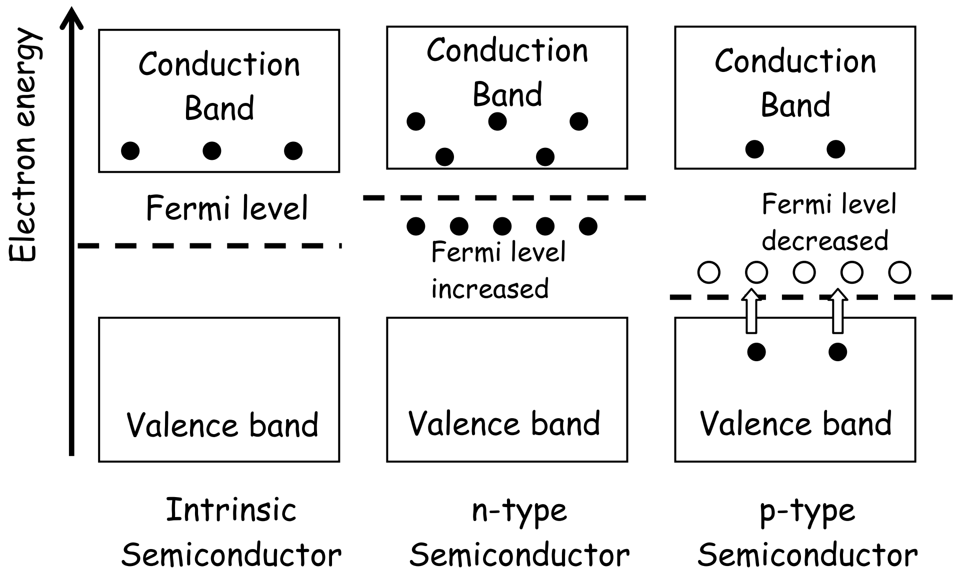
A student writes the following statements about p-type semiconductor material.

I Most charge carriers are positive
II The p-type material has a positive charge
III Impurity atoms in the material have 3 outer electrons

Which of these statements is/are true?

SQA H 2009 Q 17 (adapted)

Semiconductor Doping



Intrinsic semiconductor
The valance band is filled. The Fermi level is closer to the conduction band than in an insulator meaning that electrons which gain enough energy can move to the conduction band, allowing conduction. This can happen if the electrons gain energy through thermal excitation.

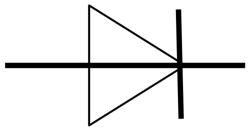
n-type semiconductor
The extra electron can move through the solid – this increases conductivity (lowers resistance), so the Fermi level moves up, closer to the conduction band. This means that the electrons require less excitation energy to move up into the conduction band.

p-type semiconductor
There is one less electron in the lattice, leaving a 'positive hole'.
The Fermi level in p-type semiconductor material moves down towards the valance band. Electrons move to fill the available holes which are just above the Fermi level.

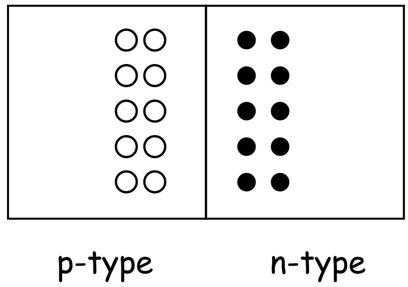
Semiconductors – p-n junction

p-n Junctions

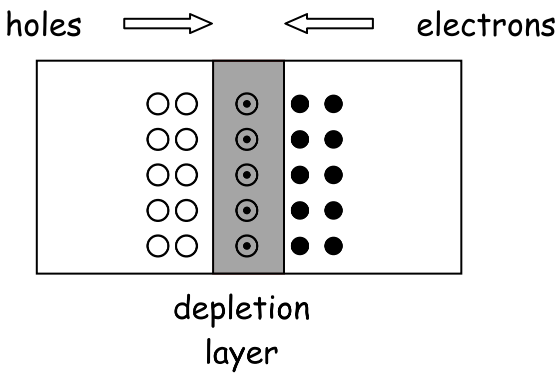
A p-n junction is created when a semiconductor is grown so that one part is n-type and the other is p-type. This forms a diode.



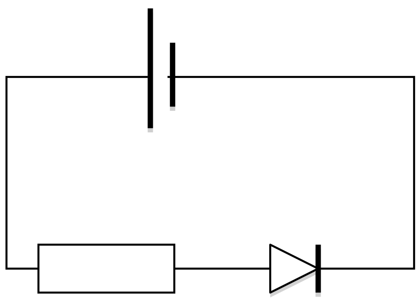
p - n



Some of the electrons move across the p-n junction to fill holes in the p-type semiconductor. Some of the holes move across the p-n junction to match electrons in the n-type semiconductor. Where holes and electrons meet they form an insulating layer, called the depletion layer.



Since some holes are on the n-type side and some electrons are on the p-type side there is a small potential difference across the depletion layer, typically 0.7V for silicon.

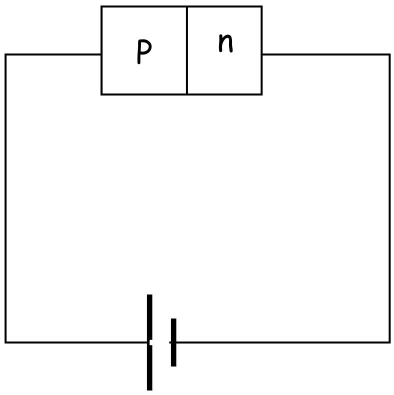


The diode must be connected the correct way round to conduct. This is called 'forward biased'.

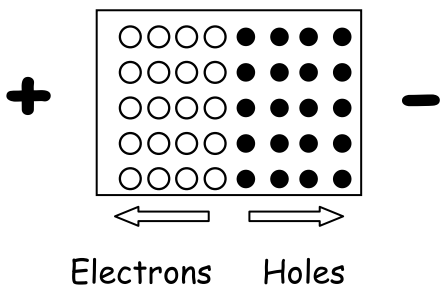
If the diode is connected the other way round (compared to the power supply) then it will not conduct and is called 'reverse biased'.

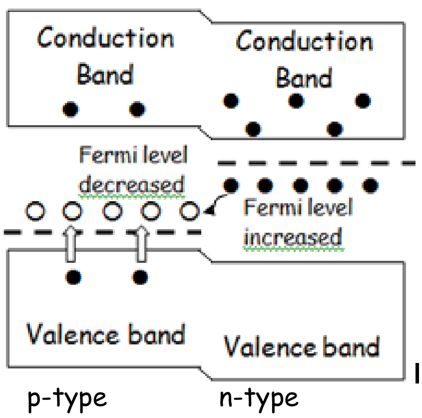
The resistor protects the diode by limiting the current through the diode.

Semiconductors – p-n junction

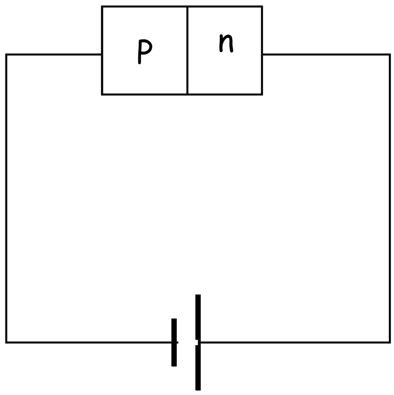


Forward biased p-n junction
CONDUCTS
Positive holes flow towards the negative terminal and the free electrons flow towards the positive terminal.
The potential difference across the junction is greater than 0.7V
(No depletion layer)

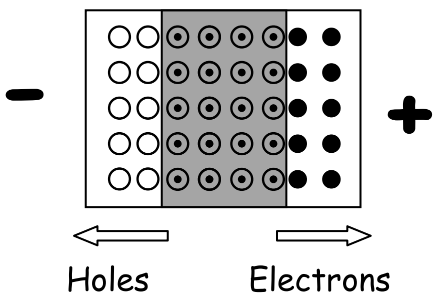


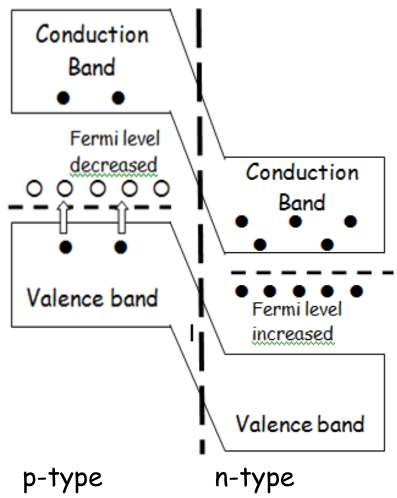


Electrons can easily flow across the depletion layer.



Reverse biased p-n junction
DOES NOT CONDUCT
Positive holes are attracted towards the negative terminal and free electrons are attracted towards the positive.
(The depletion layer gets bigger and acts as an insulator)

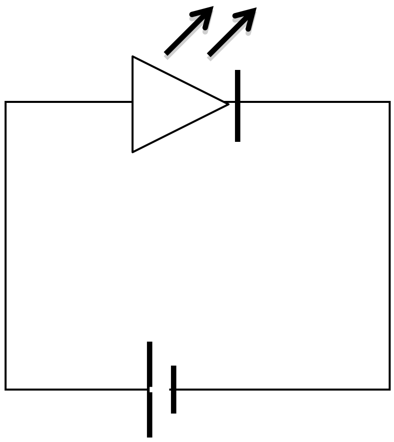




Electrons **cannot** travel across the junction.

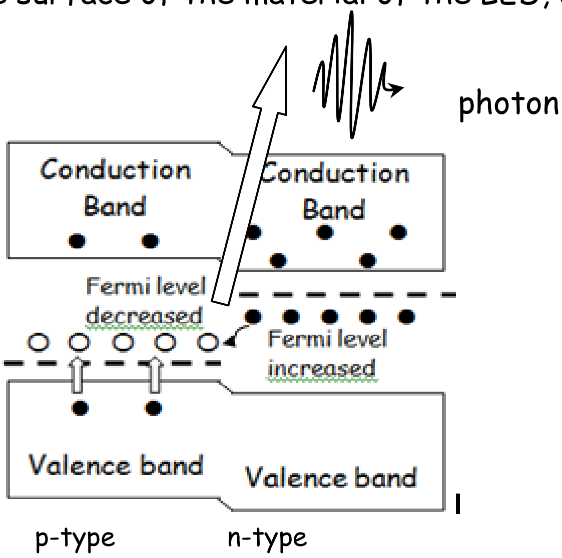
Semiconductors – Light Emitting Diode (LED)

Light Emitting Diode (LED)



The LED must be forward biased to conduct.
Typically the LED is shown in series with a resistor to limit the current through the LED/to limit the voltage

The electron moves from conduction band of n-type semiconductor to the conduction band of p-type semiconductor (across the junction).
When the electron falls from the conduction band to the valance band it loses energy. This is released as a photon of light. The junction is close to the surface of the material of the LED, allowing the light to escape.



The recombination energy of the light can be calculated if the frequency of the emitted light is measured. Energy is calculated using the formula

$E = hf$ where E = energy (Joules – J)
f = frequency (Hertz – Hz)
h = Planck's constant (6.63×10^{-34} Js)

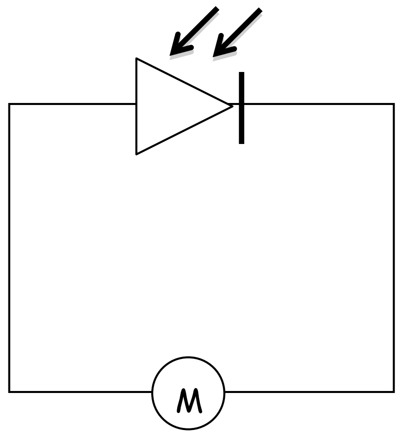
Semiconductors – Light Emitting Diode (LED)

The LED does not work in reverse bias since the charge carriers do not travel across the junction towards each other so cannot recombine.

The colour of the light emitted from the LED depends on the proportions used of each of Gallium Arsenide Phosphide. LED's can also be constructed so that they emit infra-red radiation or ultraviolet radiation.

LED's have high reliability, high efficiency and are low in cost. This means that they are being used in a large number of applications such as low energy lighting and traffic warning systems.

Semiconductors - Photodiode



Photovoltaic Mode
No bias voltage applied

Each photon incident on the junction has its energy absorbed, producing an electron-hole pair.

This results in an excess of electrons in the n-type and an excess of holes in the p-type. This causes a potential difference across the photodiode.

Increased irradiance produces increased electron-hole pairs.
Irradiance is proportional to potential difference.

A photodiode working in this mode is referred to as a photocell.
This forms the basis of a solar cell used in calculators and satellites, but is limited to low power applications.

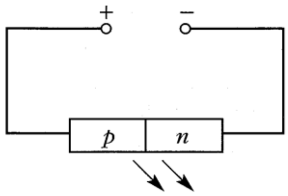
Semiconductors

Example 40

(a) A sample of pure semiconducting material is doped by adding impurity atoms.
How does this addition affect the resistance of the semiconducting material.?

The resistance decreases

(b) Light of frequency 6.7×10^{14}Hz is produced at the junction of a light emitting diode (LED)



(i) Describe how the movement of charges in a forward-biased LED produces light. Your description should include the terms: *electrons; holes; photons and junctions.*
Electrons recombine with holes at the junction to releasing photons

(ii) Calculate the wavelength of the light emitted from the LED

$$\lambda = \frac{v}{f} = \frac{3 \times 10^8}{6.7 \times 10^{14}} = 448\text{nm}$$

(iii) Use information from the data sheet to deduce the colour of the light.
Blue to blue-violet

(c) Calculate the minimum potential difference across the p-n junction when it emits photons of light

$E = hf = 6.63 \times 10^{-34} \times 6.7 \times 10^{14} =$

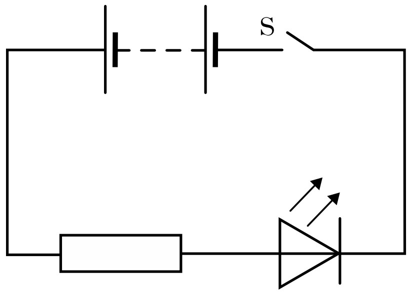
$E = QV \Rightarrow \quad = 1.6 \times 10^{-19} \times V$

$V =$

SQA H 2002 Q29, H 2006, Q27, H 2004 Q 29 – all adapted.

Semiconductors

Example 41
An LED is connected as shown.



When switch S is closed

A the p-n junction is reverse biased and free charge carriers are produced which may recombine to give quanta of radiation

B the p-n junction is forward biased and positive and negative charge carriers are produced by the action of light

C the p-n junction is reverse biased and positive and negative charge carriers are produced by the action of light

D the p-n junction is forward biased and positive and negative charge carriers may recombine to give quanta of radiation

E the p-n junction is reverse biased and positive and negative charge carriers may recombine to give quanta of radiation

SQA H 2010 Q16

Example 42
A p-n junction is forward biased.

Positive and negative charge carriers recombine in the junction region. This causes the emission of

A a hole
B an electron
C an electron-hole pair
D a proton
E a photon

SQA H 2009 Q 18