Higher Physics
Electricity Unit
St Andrew's Academy

This booklet has notes and space for completing worked examples on the Electricity Unit and covers the following key areas:

1. Monitoring and measuring a.c.
2. Current, potential difference, power and resistance
3. Internal resistance
4. Internal resistance & EMF from a graph
5. Capacitance
6. Energy in a capacitor
7. Charge and discharge graphs
8. Conductors, semiconductors and insulators
9. p-n junctions

DATA SHEET

COMMON PHYSICAL QUANTITIES

Quantity	*Symbol*	*Value*	*Quantity*	*Symbol*	*Value*
Speed of light in vacuum	c	$3 \cdot 00 \times 10^{8}$ m s^{-1}	Planck's constant	h	$6 \cdot 63 \times 10^{-34}$ J s
Magnitude of the charge on an electron	e	$1 \cdot 60 \times 10^{-19}$ C	Mass of electron	m_e	$9 \cdot 11 \times 10^{-31}$ kg
Universal Constant of Gravitation	G	$6 \cdot 67 \times 10^{-11}$ m^{3} kg^{-1} s^{-2}	Mass of neutron	m_n	$1 \cdot 675 \times 10^{-27}$ kg
Gravitational acceleration on Earth	g	$9 \cdot 8$ m s^{-2}	Mass of proton	m_p	$1 \cdot 673 \times 10^{-27}$ kg
Hubble's constant	H_0	$2 \cdot 3 \times 10^{-18}$ s^{-1}			

REFRACTIVE INDICES

The refractive indices refer to sodium light of wavelength 589 nm and to substances at a temperature of 273 K.

Substance	*Refractive index*	*Substance*	*Refractive index*
Diamond	2·42	Water	1·33
Crown glass	1·50	Air	1·00

SPECTRAL LINES

Element	*Wavelength/nm*	*Colour*	*Element*	*Wavelength/nm*	*Colour*
Hydrogen	656	Red	Cadmium	644	Red
	486	Blue-green		509	Green
	434	Blue-violet		480	Blue
	410	Violet	Lasers		
	397	Ultraviolet	*Element*	*Wavelength/nm*	*Colour*
	389	Ultraviolet	Carbon dioxide	9550 10590	Infrared
Sodium	589	Yellow	Helium-neon	633	Red

PROPERTIES OF SELECTED MATERIALS

Substance	*Density/kg m^{-3}*	*Melting Point/K*	*Boiling Point/K*
Aluminium	$2 \cdot 70 \times 10^{3}$	933	2623
Copper	$8 \cdot 96 \times 10^{3}$	1357	2853
Ice	$9 \cdot 20 \times 10^{2}$	273	....
Sea Water	$1 \cdot 02 \times 10^{3}$	264	377
Water	$1 \cdot 00 \times 10^{3}$	273	373
Air	1·29	....	....
Hydrogen	$9 \cdot 0 \times 10^{-2}$	14	20

The gas densities refer to a temperature of 273 K and a pressure of $1 \cdot 01 \times 10^{5}$ Pa.

Relationships required for Physics Higher

$d = \bar{v}t$

$s = \bar{v}t$

$v = u + at$

$s = ut + \frac{1}{2}at^2$

$v^2 = u^2 + 2as$

$s = \frac{1}{2}(u+v)t$

$W = mg$

$F = ma$

$E_W = Fd$

$E_p = mgh$

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

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

$p = mv$

$Ft = mv - mu$

$F = G\frac{m_1 m_2}{r^2}$

$t' = \frac{t}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$

$l' = l\sqrt{1-\left(\frac{v}{c}\right)^2}$

$f_o = f_s\left(\frac{v}{v \pm v_s}\right)$

$z = \frac{\lambda_{observed} - \lambda_{rest}}{\lambda_{rest}}$

$z = \frac{v}{c}$

$v = H_0 d$

$W = QV$

$E = mc^2$

$E = hf$

$E_k = hf - hf_0$

$E_2 - E_1 = hf$

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

$v = f\lambda$

$d\sin\theta = m\lambda$

$n = \frac{\sin\theta_1}{\sin\theta_2}$

$\frac{\sin\theta_1}{\sin\theta_2} = \frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2}$

$\sin\theta_c = \frac{1}{n}$

$I = \frac{k}{d^2}$

$I = \frac{P}{A}$

$V_{peak} = \sqrt{2}V_{rms}$

$I_{peak} = \sqrt{2}I_{rms}$

$Q = It$

$V = IR$

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

$R_T = R_1 + R_2 + ...$

$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + ...$

$E = V + Ir$

$V_1 = \left(\frac{R_1}{R_1 + R_2}\right)V_s$

$\frac{V_1}{V_2} = \frac{R_1}{R_2}$

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

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

path difference $= m\lambda$ or $\left(m + \frac{1}{2}\right)\lambda$ where $m = 0, 1, 2...$

random uncertainty $= \dfrac{\text{max. value} - \text{min. value}}{\text{number of values}}$

1. Monitoring and measuring a.c.

Learning outcomes:

- A.C as a current which changes direction and instantaneous value with time
- Calculations involving peak and r.m.s. values
- Determination of frequency from graphical data

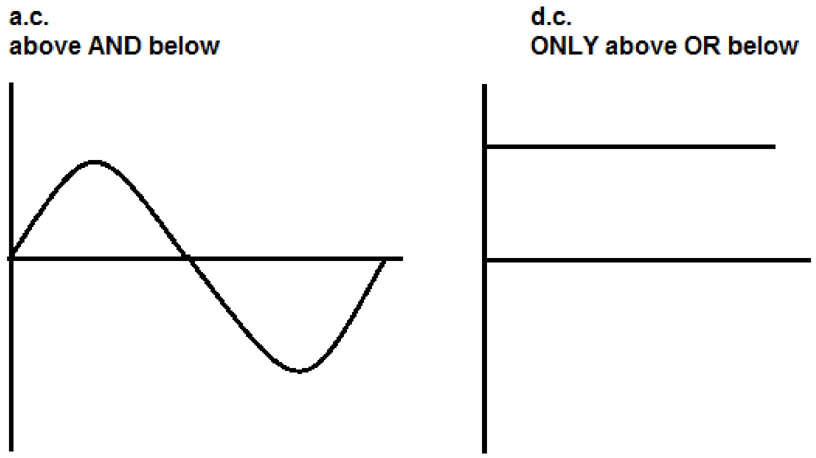
Background revision (a.c. and d.c.)

- There are two types of electrical current:

1. **Direct Current (d.c.)** where the current only travels in one direction **eg a battery.**
2. **Alternating Current (a.c.)** where the current is constantly changing direction **eg the mains socket.**

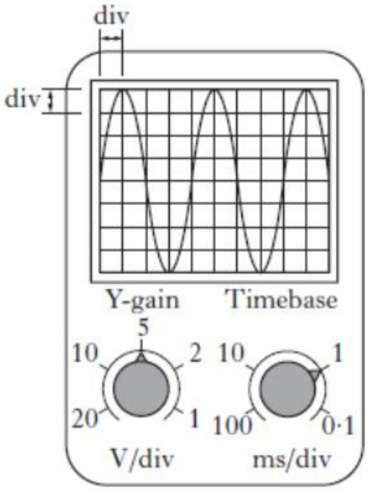
Background revision (oscilloscope)

- An electronic device called an oscilloscope can be used to draw a graph of the electrical signal of both a.c. and d.c.



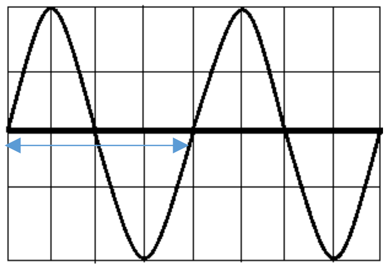
Using an oscilloscope

- Oscilloscopes have dials on them to allow you to calibrate two things about the signal produced:
- On the x-axis – time per cm (time base often given in ms)
- On the y-axis – volts per cm (voltage gain often given in mV)



Period of a wave

- The period of a wave is the time taken for one complete wave to pass a point.
- It has the symbol T and is measured in s.
- For example, if we have an oscilloscope **set to 1ms cm^{-1}** (a time of 1ms for each gridline 1 cm apart) as shown:



- Then we can see that one complete wave is made after **<u>4 boxes</u>**.
- Therefore the period of 1 wave, T = 4 x 1ms = 4ms:
- T = 4 x 10^{-3} s

Measuring the frequency of a wave

- Once we have established the period of a wave, T, using the method above, we can find the frequency of a wave, f, by the equation:
- $f = \frac{1}{T}$

Experiment

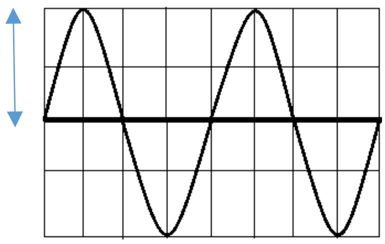
Frequency on signal generator (Hz)	Period of one wave, T (s)	Frequency calculated f = 1 / T (Hz)

Peak voltage

- When we consider voltage there are two values that we must consider:

1. Peak voltage
2. R.m.s. voltage (root mean square voltage)

- Peak voltage is "always bigger" than r.m.s. voltage
- The value quoted for the mains (230V) is the r.m.s. value.
- **The r.m.s. voltage of an a.c. value is equivalent to the d.c. value e.g. an r.m.s of 230V a.c = 230V d.c.**
- Oscilloscope traces show the peak voltage of a wave, consider the following oscilloscope trace:
- (the y-gain setting is set to 0.1 V cm^{-1})



- The amplitude shown is 2 cm. Therefore the peak voltage is 2 x 'volts per cm' setting on the control.
- 2 x 0.1v cm^{-1} = 0.2 V

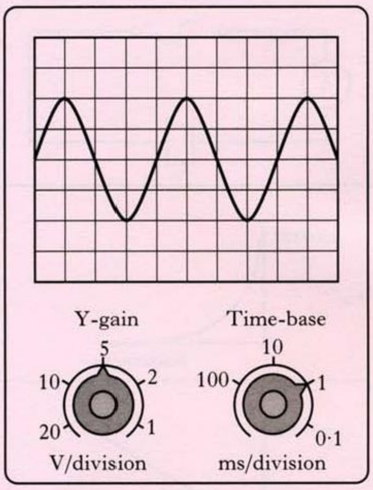
Peak and r.m.s. formulae

- The peak voltage and r.m.s. voltage are related by:
- $V_{peak} = \sqrt{2}\ V_{r.m.s}$
- Peak current and r.m.s current have a similar relationship:
- $I_{peak} = \sqrt{2}\ I_{r.m.s}$

Mulitiple choice Examples:

Old Higher 2004 Qu: 12:

12. The output from a signal generator is connected to the input terminals of an oscilloscope. The trace observed on the oscilloscope screen, the Y-gain setting and the time-base setting are shown in the diagram.



The frequency of the signal shown is calculated using the

A Y-gain setting and the vertical height of the trace

B Y-gain setting and the horizontal distance between the peaks of the trace

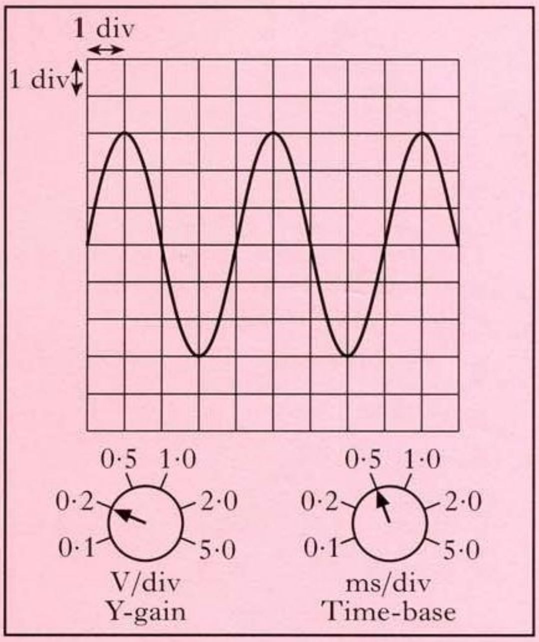
C Y-gain setting and time-base setting

D time-base setting and the vertical height of the trace

E time-base setting and the horizontal distance between the peaks of the trace.

Old Higher 2005 Qu: 9

9. An a.c. signal is displayed on an oscilloscope screen. The Y-gain and time-base controls are set as shown.



The frequency of the signal is

A 0·50 Hz

B 1·25 Hz

C 2·00 Hz

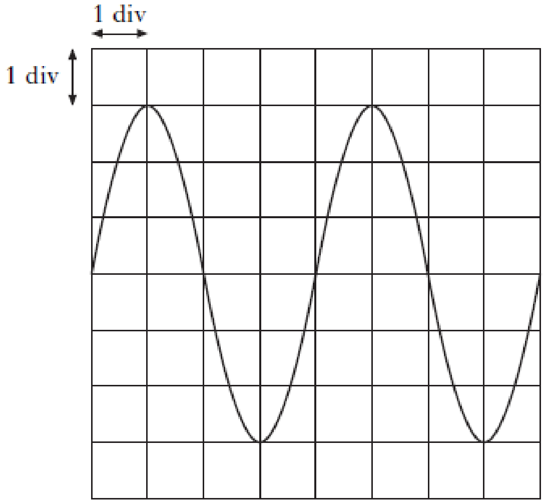
D 200 Hz

E 500 Hz.

Old Higher 2007 Qu: 10:

10. A signal from a power supply is displayed on an oscilloscope.

The trace on the oscilloscope is shown.



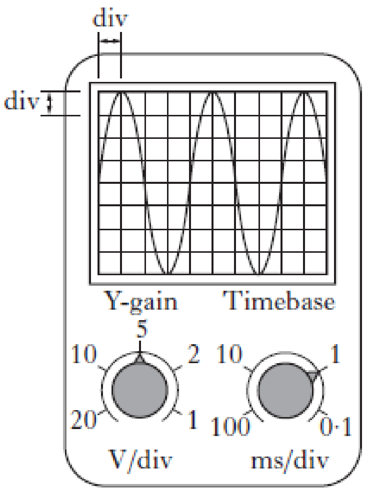
The time-base is set at 0·01 s/div and the Y-gain is set at 4·0 V/div.

Which row in the table shows the r.m.s. voltage and the frequency of the signal?

	r.m.s. voltage/V	*frequency*/Hz
A	8·5	25
B	12	25
C	24	25
D	8·5	50
E	12	50

Revised Higher 2012 Qu: 19

19. An alternating voltage is displayed on an oscilloscope screen. The Y-gain and the timebase settings are shown.



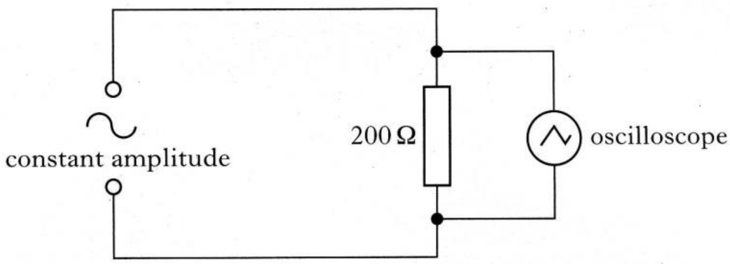
Which row in the table gives the values for the peak voltage and frequency of the signal?

	Peak voltage/V	*Frequency*/Hz
A	10	100
B	10	250
C	20	250
D	10	500
E	20	1000

Paper 2 Examples:

Old Higher 2000 – Qu: 26

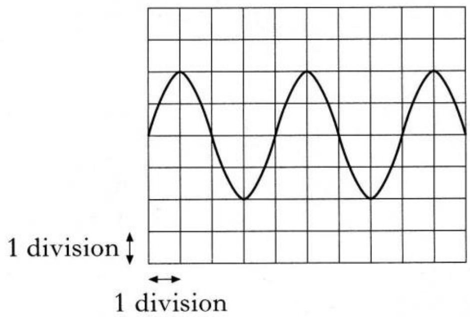
26. A circuit is set up as shown below. The amplitude of the output voltage of the a.c. supply is kept constant.



The settings of the controls on the oscilloscope are as follows:

y-gain setting = 5 V/division
time-base setting = 2·5 ms/division

The following trace is displayed on the oscilloscope screen.



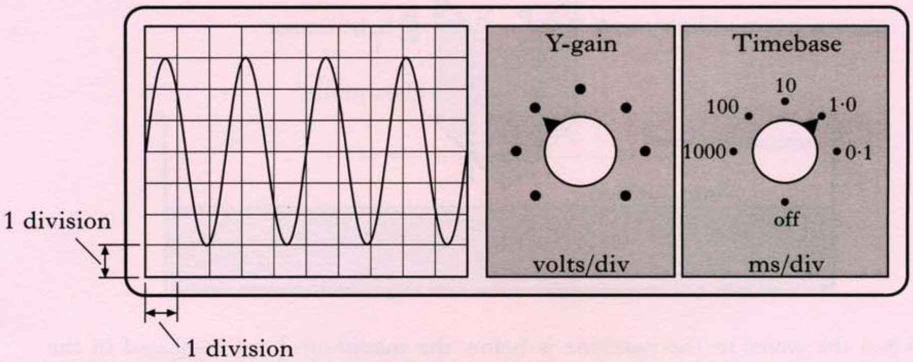
(*a*) (i) Calculate the frequency of the output from the a.c. supply.

(ii) Calculate the **r.m.s. current** in the 200 Ω resistor. **5**

Old Higher 2003 Qu: 25

25. (*a*) A signal generator is connected to an oscilloscope. The output of the signal generator is set to a peak voltage of 15 V.

The following diagram shows the trace obtained, the Y-gain and the timebase controls on the oscilloscope. The scale for the Y-gain has been omitted.



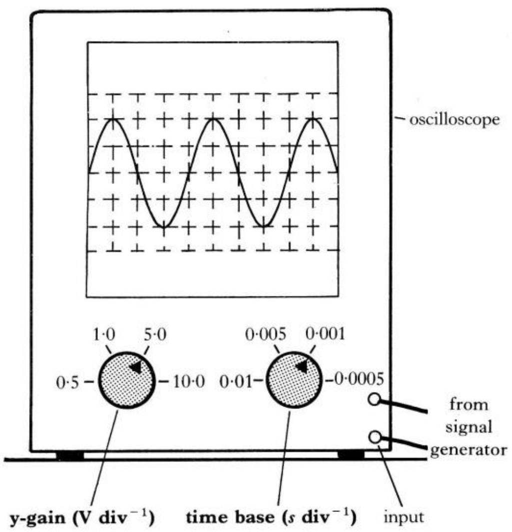
Calculate:

(i) the Y-gain setting of the oscilloscope;

(ii) the frequency of the signal in hertz. **3**

Measuring and measuring a.c. homework **Due date:________________**

1. The diagram below shows the screen and the settings of an oscilloscope, which is being used to measure the output frequency of a signal generator.



What is the frequency of the signal applied to the input of the oscilloscope?

A 2.5 Hz

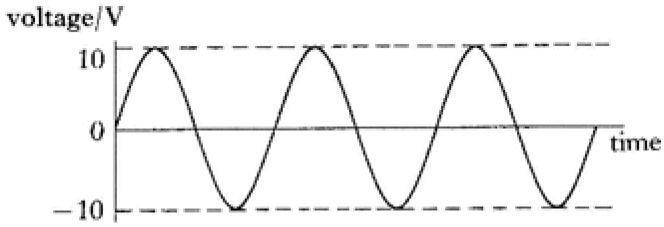
B 12.5 Hz

C 40 Hz

D 250 Hz

E 500 Hz

2. The diagram below represents an alternating voltage.



What d.c. supply voltage would produce the same rate of heating from this heater?

A 5 V

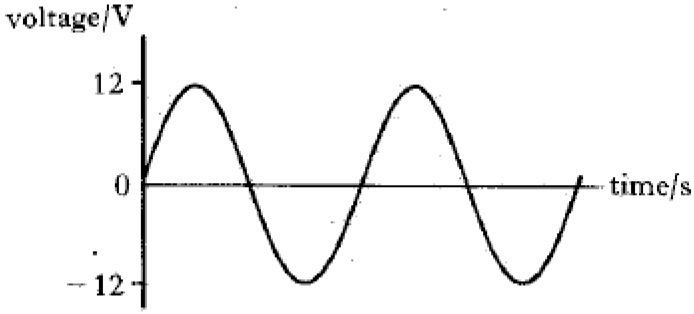
B 10 / √ 2 V

C 10 V

D 10 √ 2 V

E 20 V

3. An immersion heater can be operated either from an a.c. supply or a d.c. supply. The graph below represents the a.c. supply voltage.



What d.c. supply voltage would produce the same rate of heating from this heater?

A 6 V

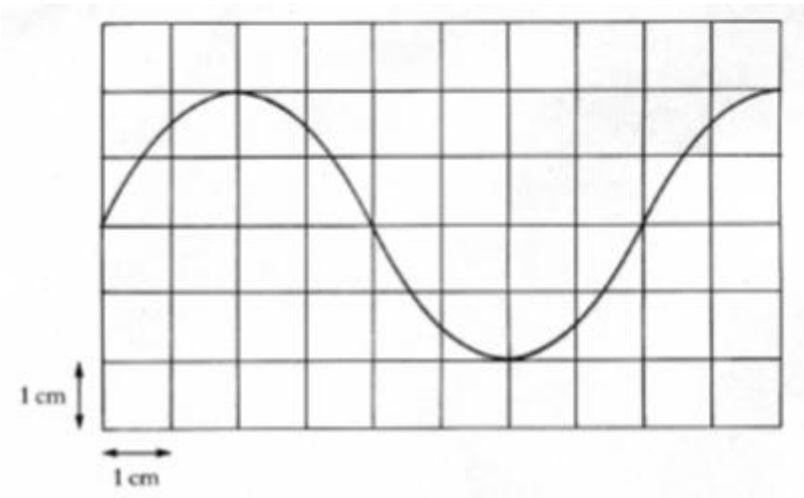
B 12 / √ 2 V

C 12 V

D 12 √ 2 V

E 24 V

4. An oscilloscope is connected across a resistor in a circuit. The trace obtained is shown below.



The peak voltage shown on the oscilloscope is 10 volts and the time base setting is 0.2 ms cm^{-1}. Calculate:

(a) The r.m.s. voltage across the resistor
(b) The frequency of the a.c. voltage.

2. Current, potential difference, resistance and power:

Learning Outcomes:

- Use relationships involving potential difference, current, resistance and power to analyse circuits.
- Calculations may involve several steps.
- Calculations involving potential dividers circuits.

Ohm's Law:

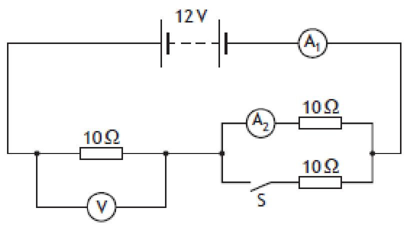
- The constant proportion of voltage v current is defined to be the resistance.
- $R = \frac{V}{I}$ or $V = IR$
- This is known as Ohm's Law.

Circuit rules:

Quantity	Definition	Series	Parallel
Current	Flow of electric charges	$I_s = I_2 = I_3 = I_4$	$I_p = I_1 + I_2 + I_3$
Voltage	Energy given to each charge	$V_s = V_1 + V_2 + V_3$	$V_p = V_1 = V_2 = V_3$
Resistance	The limit of electrical current	$R_s = R_1 + R_2 + R_3$	$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$

CfE 2018 Qu:

15. A circuit is set up as shown.



The battery has negligible internal resistance.

A student makes the following statements about the readings on the meters in this circuit.

I When switch S is open the reading on the voltmeter will be 6·0 V.

II When switch S is open the reading on A_2 will be 0·60 A.

III When switch S is closed the reading on A_1 will be 0·80 A.

Which of these statements is/are correct?

A I only

B II only

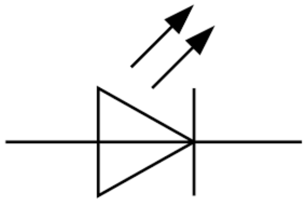
C I and II only

D II and III only

E I, II and III

Light Emitting Diodes (LEDs):

- LED stands for Light Emitting Diode.
- Transforms Electrical → Light Energy
- It has the following symbol.
- (you must know how to draw this)

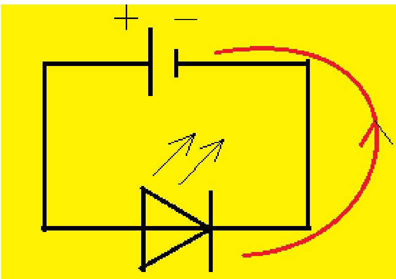


Using an LED correctly:

- Build a simple circuit involving a battery and a bulb.
- Change the direction of the bulb. Does it still light?
- Repeat the above for an LED.

Output Device	Does it light in both directions?
Lamp	
LED	

- Therefore, an LED only works in one direction (the arrow points to the negative terminal).

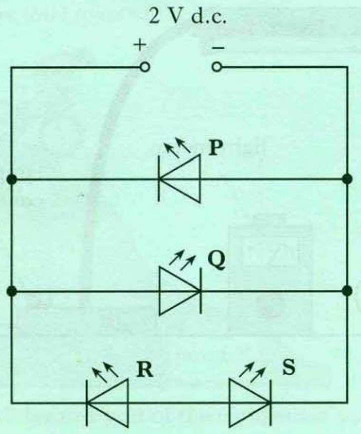


What happens if there are several LEDs facing different directions?

- If one LED is facing the positive terminal that will block any current passing through it.
- Therefore if we have two LED's in series, facing opposite directions then none of them will work.

Example:

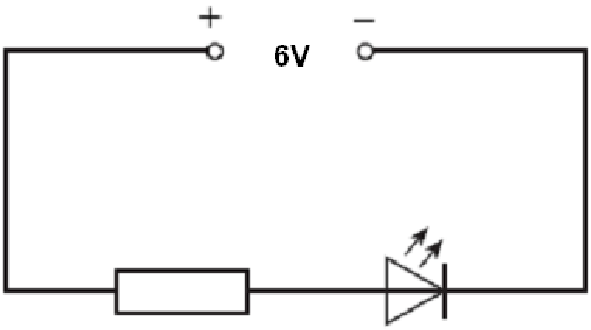
(*d*) The student now connects some LEDs to a 2 V d.c. supply as shown.



Which of the LEDs P, Q, R and S will light? **1**

Worked example:

- The LED in the circuit requires 1.5 V to operate when the current is 200mA. Find the value of the fixed resistor.



Two resistors in parallel:

- For two and only two resistors in parallel, the following formula can be used to calculate total resistance, R_T:

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

Note - This is not in the rel. sheet.

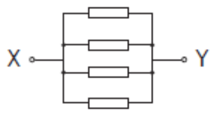
Combining Resistance:

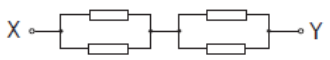
- In a series circuit, the total resistance is always bigger than the biggest resistor.
- In a parallel circuit, the total resistance is always smaller than the smallest resistor.

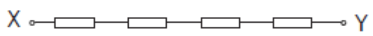
Multiple-choice Example - CfE Specimen Qu: 14:

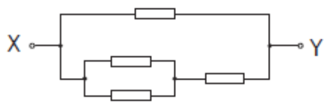
14. In the diagrams below, each resistor has the same resistance.

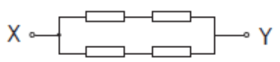
Which combination has the least value of the effective resistance between the terminals X and Y?

A 

B 

C 

D 

E 

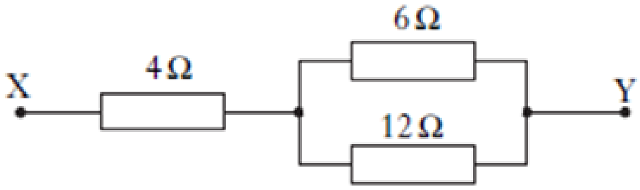
What if we have both?:

- If we have both parallel and series resistors in a circuit;

1. Work out any resistors that are in series in the same branch.
2. Then work out resistors in parallel and replace them with the value of one resistor.
3. Work out the resistors in series.

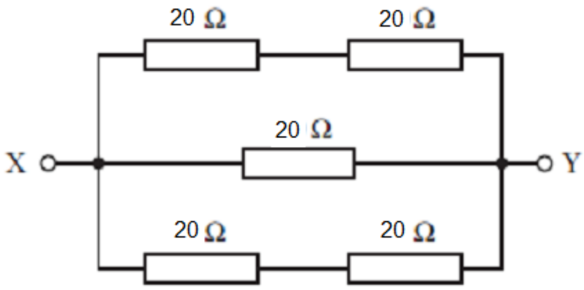
Worked Example 1:

- Calculate the total resistance between X and Y.



Worked Example 2:

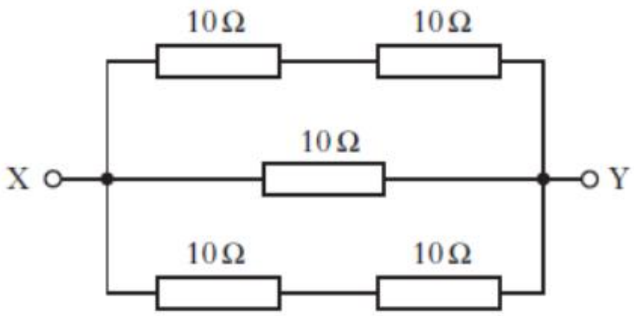
- Calculate the total resistance between X and Y.



Multiple choice Examples:

Revised Higher 2012 Qu: 8

18. The diagram shows part of an electrical circuit.



What is the resistance between X and Y?

A 0·2 Ω

B 5 Ω

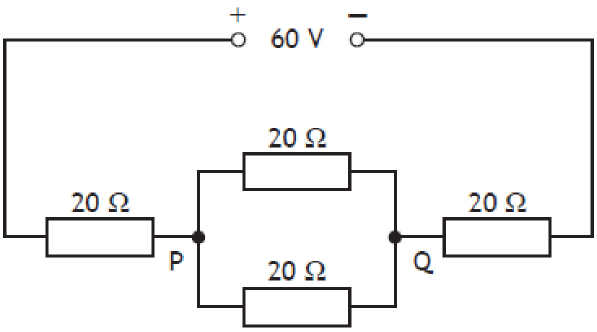
C 10 Ω

D 20 Ω

E 50 Ω

CfE Specimen Higher Qu: 19

19. Four resistors each of resistance 20 Ω are connected to a 60 V supply of negligible internal resistance as shown.



The potential difference across PQ is

A 12 V

B 15 V

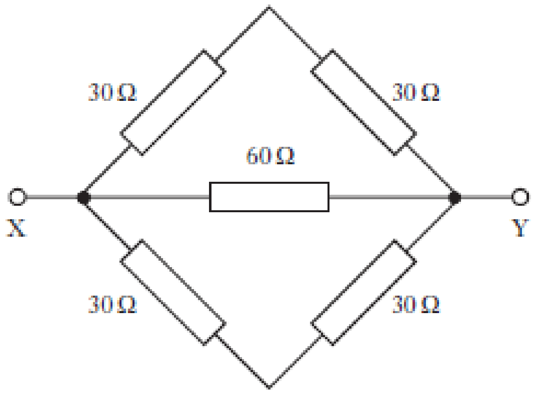
C 20 V

D 24 V

E 30 V.

Revised Higher 2014 Qu: 18

16. Five resistors are connected as shown.



The resistance between X and Y is

A 12 Ω

B 20 Ω

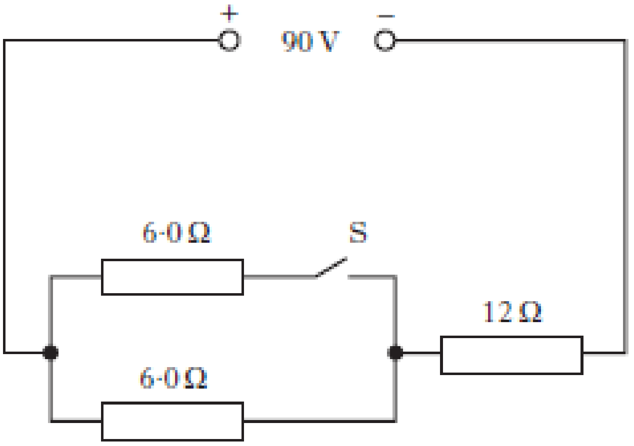
C 30 Ω

D 60 Ω

E 180 Ω.

Old Higher 2014 Qu: 17:

17. A circuit is set up as shown.



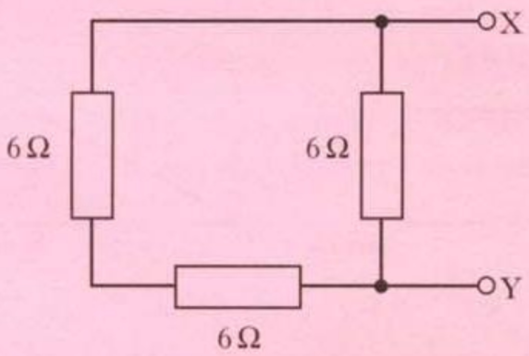
The internal resistance of the supply is negligible.

Which row in the table shows the potential difference (p.d.) across the 12 Ω resistor when switch S is open and when S is closed?

	p.d. across 12 Ω resistor when S is open/V	*p.d. across 12 Ω resistor when S is closed/V*
A	30	18
B	45	45
C	60	45
D	60	72
E	72	60

Old Higher 2006 Qu: 8:

8. Three resistors are connected as shown.



The total resistance between X and Y is

A 2 Ω

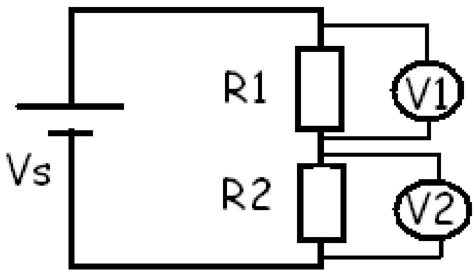
B 4 Ω

C 6 Ω

D 9 Ω

E 18 Ω.

Potential Dividers:



- A potential divider circuit is a series circuit where the voltage (potential) is split between two resistors.
- It is also known as a **voltage divider.**
- It is often shown on its side:

Formula 1: When the supply voltage, Vs, is not known:

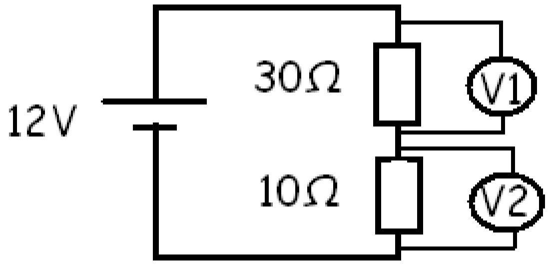
$$\frac{R_1}{R_2} = \frac{V_1}{V_2}$$

Formula 2: When the supply voltage, Vs, is know:

- Given in relationship sheet: $V_2 = \frac{R_2}{(R_1 + R_2)} \times V_S$
- Not given in relationship sheet: $V_1 = \frac{R_1}{(R_1 + R_2)} \times V_S$

Worked example:

Find the voltage across both resistors (V_1 and V_2):



- $V_2 = \frac{R_2}{R_1+R_2} \times V_S$

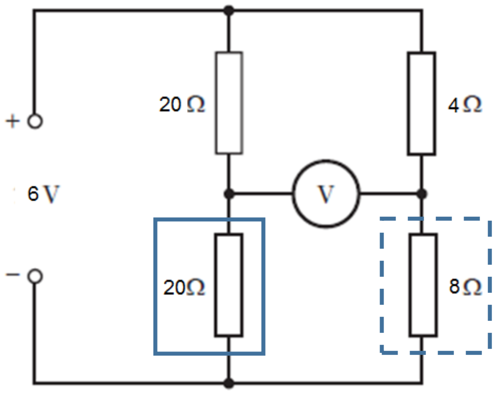
  $= \frac{10}{30 + 10} \times 12$

  $=$ **3 V**

- V_1 can then just be calculated using formula for voltage in series: $V_s = V_1 + V_2$
- So $V_1 = 12 - 3 =$ **9V**

What if we have two potential dividers in parallel?

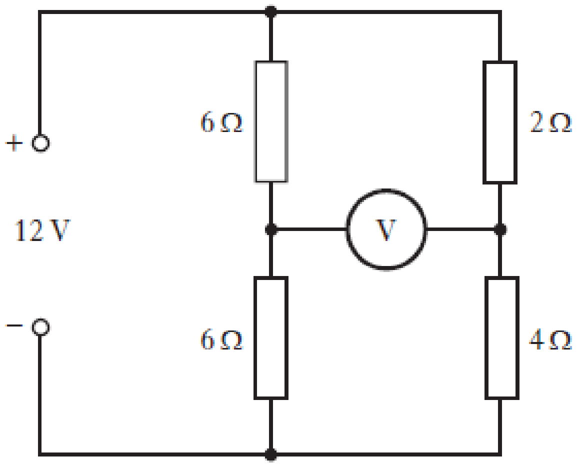
1. Work out the voltage of R_2 on each branch.
2. The reading on the voltmeter is the difference between the two.



Worked Example – find the reading on the voltmeter in the circuit above:

Multiple-choice Example 2013 Qu: 7:

17. The following circuit is set up.



The reading on the voltmeter is

A 0 V

B 2 V

C 6 V

D 8 V

E 12 V.

Power:

- Power (P) is defined as the rate of energy transferred per second.
- It is measured in Watts.
- There are several different formulae that can be used for electric power.
- $P = IV$
- $P = I^2 R$
- $P = \frac{V^2}{R}$
- $P = \frac{E}{t}$
- (the formula $V = IR$ can also be used to work out any unknown values)

CfE Higher 2018:

16. The power dissipated in a 120 Ω resistor is 4·8 W.

The current in the resistor is

A 0·020 A

B 0·040 A

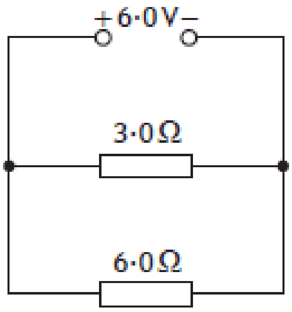
C 0·20 A

D 5·0 A

E 25 A.

CfE Higher 2019:

23. A circuit is set up as shown.



The power supply has negligible internal resistance.

The power dissipated in the 3·0 Ω resistor is

A 3·0 W

B 6·0 W

C 9·0 W

D 12 W

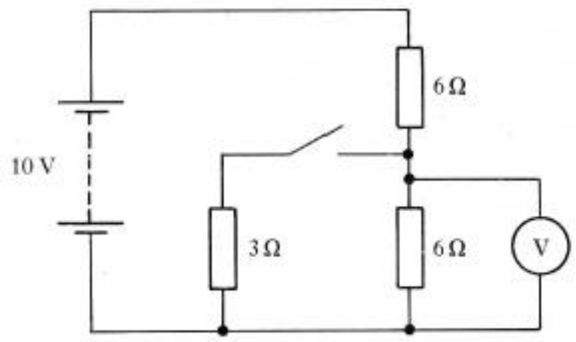
E 18 W.

Current, potential difference, resistance and power homework:

Due date:

1.

The circuit below shows resistors connected as a potential divider.



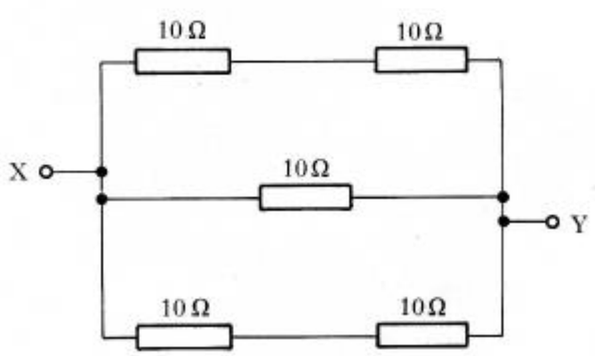
Calculate the reading on the voltmeter

(*a*) when the switch is open;

(*b*) when the switch is closed.

2.

The diagram below shows part of an electrical circuit.



What is the resistance between X and Y?

A 0·2 Ω

B 5 Ω

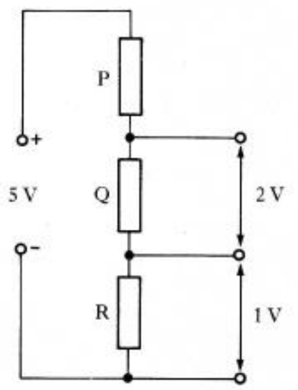
C 10 Ω

D 20 Ω

E 50 Ω

3.

The circuit shown below is used to provide potential differences of 2 volts and 1 volt from a 5 volt supply with zero internal resistance.

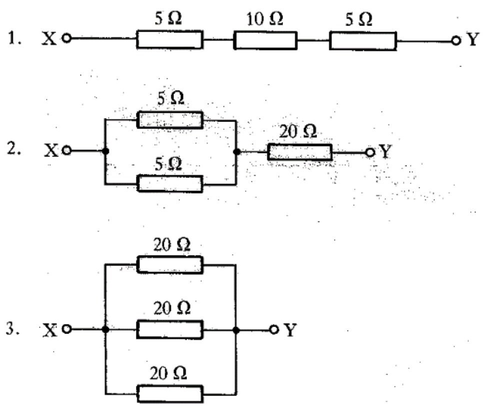


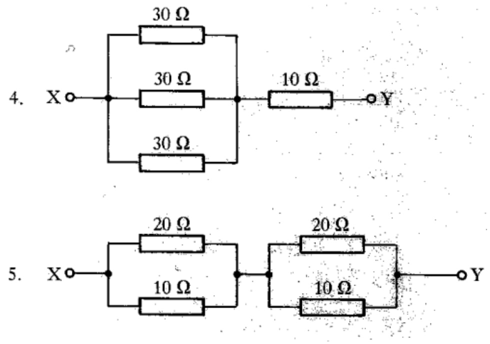
Which of the following gives possible values, in kilohms, for resistors P, Q and R?

	P	Q	R
A	1	1	2
B	2	1	2
C	2	2	1
D	3	2	2
E	3	2	3

4.

In which of the following arrangements of resistors is the resistance between X and Y the same?





A 1 and 2 only

B 1 and 3 only

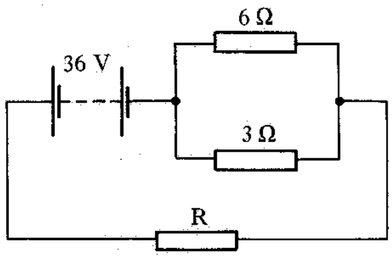
C 1 and 4 only

D 1, 2 and 4 only

E 1, 3 and 5 only

5.

The current delivered by the battery in the following circuit is 3 A.



Assuming that the battery has negligible internal resistance, the resistance of resistor R is

A 3 Ω

B 4 Ω

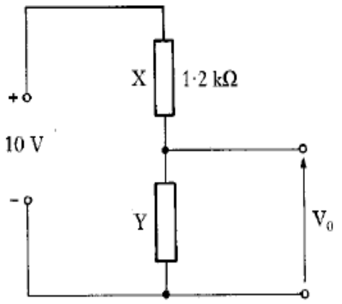
C 10 Ω

D 12 Ω

E 18 Ω.

6.

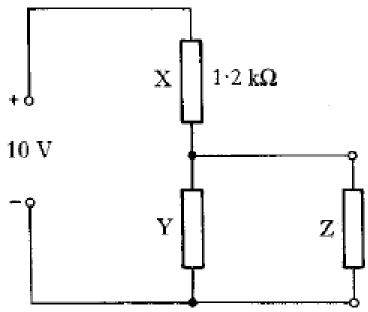
(*a*) A potential divider is used to provide an output voltage V_0 from a 10 V supply as shown below. The supply has negligible internal resistance.



(i) The resistance of resistor X is 1·2 kΩ and the output voltage required is 6·0 V.

Calculate the resistance of resistor Y.

(ii) A load resistor Z is now connected across the output as shown below.



Explain why the voltage across Z is less than 6·0 V.

(iii) Calculate the voltage across resistor Z when its resistance is 4·7 kΩ.

3. Internal resistance:

Learning outcomes:

- Electromotive force, internal resistance and terminal potential difference. Ideal supplies, short circuits and open circuits.

Electromotive Force (E.M.F.):

- An electric field applied to a conductor causes the free electric charges in it to move.

- The **e.m.f.** (symbol E) of a source is the electric potential **energy** supplied to each coulomb of **charge** which passes through the source.

- The **p.d.** (potential difference – symbol V) is the **work** required to push each coulomb of **charge** through a resistor.

  (In resistors the work becomes heat.)

- For example, an EMF of 6 V means that there is 6J of energy given to each coulomb of charge.

Multiple-choice example – 2008 Qu: 9:

9. The e.m.f. of a battery is

   A the total energy supplied by the battery

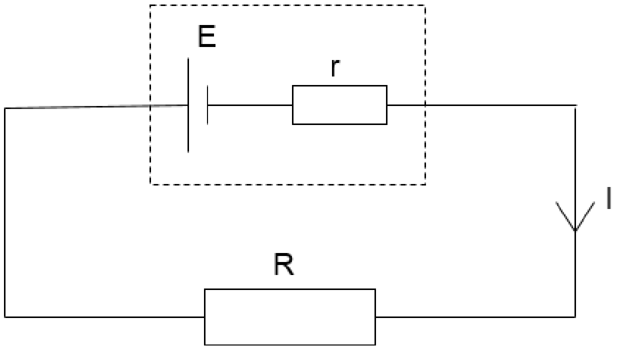
   B the voltage lost due to the internal resistance of the battery

   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.

Internal Resistance:



- Real cells and batteries have internal resistance.
- An electrical source is equivalent to a source of e.m.f. (electro-motive force) with a resistor in series (internal resistance).

$$E = IR + Ir$$

E: e.m.f; IR: terminal potential difference; Ir: 'lost volts'

R = load resistor
r = Internal resistance
I = current

- Remember!!! E.m.f. is measured in VOLTS.
- The 'lost volts' increase with the current.
- E.m.f. can also be defined by explaining the equation above

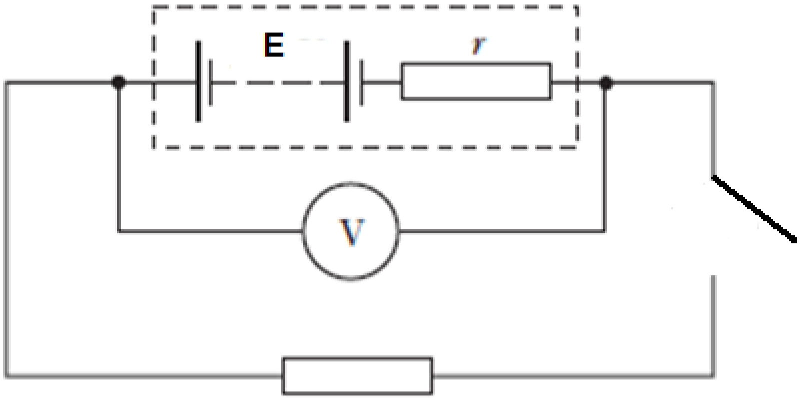
  ie terminal potential difference + lost volts

The short circuit current:

- This is the current when the circuit shorts across the battery terminal.
- It can be found using Ohm's Law with the EMF and the internal resistor:

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

What does the voltmeter read?

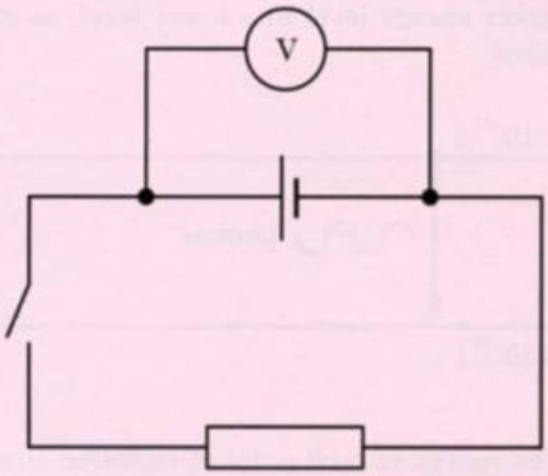


- The voltmeter can provide two pieces of information depending on whether the switch is open or closed:
- Open switch – voltmeter provides EMF, E (known as open circuit p.d.)
- Closed switch – voltmeter provides t.p.d, V (voltage across load resistor, R)

- REMEMBER! With values for both EMF (E) and tpd (V) you can now work out lost volts (Ir): lost volts = E – V

Multiple-choice example 2002 Qu: 10:

10. A student sets up the following circuit.



When the switch is open, the student notes that the reading on the voltmeter is 1·5 V. The switch is then closed and the reading falls to 1·3 V.

The decrease of 0·2 V is referred to as the

A e.m.f.

B lost volts

C peak voltage

D r.m.s. voltage

E terminal potential difference.

Tackling problems:

- Problems will always give at least **three** of the possible **six** factors in the question:

- E = V
- I = A (= E / R+r)
- R = Ω
- r = Ω
- tpd = V (=IR)
- lost volts = V (=Ir)

Always use V = IR

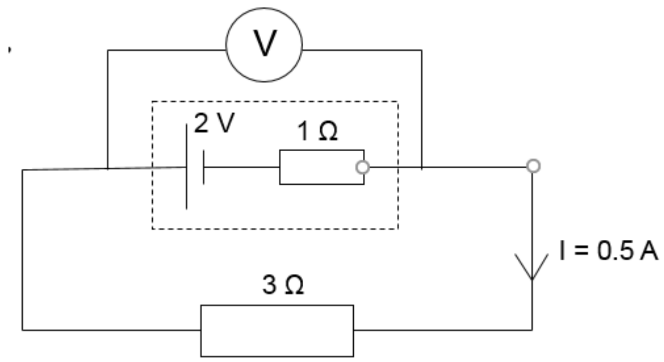
- V = IR can be used to help you find the tpd and lost volts:

V	=	I R
tpd	=	I R (load resistor)
lost v	=	I r (internal resistor)

- Remember if you have trouble working out any values then try using V = IR as above

Worked Example:

The voltmeter reads the terminal potential difference (t.p.d.). What will the voltmeter read in the above circuit?



Common PS question:

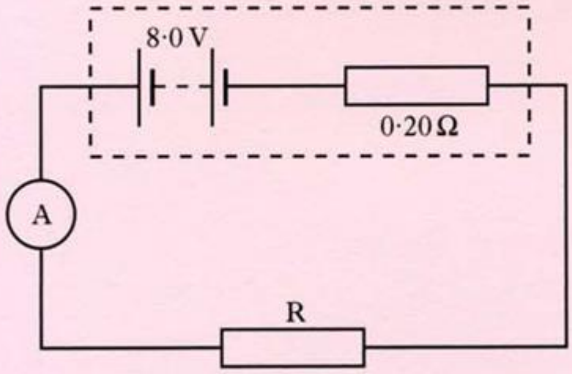
A second resistor will be placed in parallel with the load resistor (R), what happens to the reading on the voltmeter?

- 2 resistors in parallel means R_T down
- So I up
- Lost volts up
- Voltmeter reading down

Multiple-choice examples

Old Higher 2003 Qu: 9:

9. In the following circuit, the battery has an e.m.f. of 8·0 V and an internal resistance of 0·20 Ω.



The reading on the ammeter is 4·0 A.

The resistance of R is

A 0·5 Ω

B 1·8 Ω

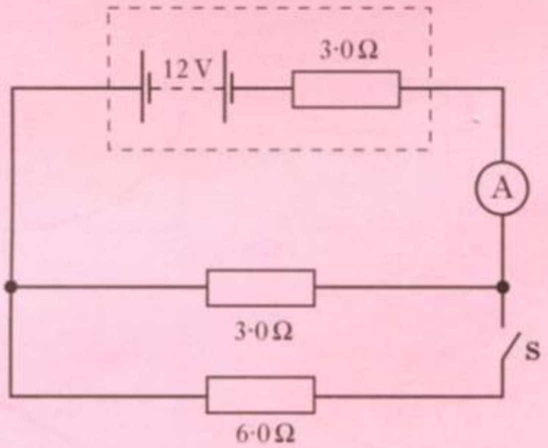
C 2·0 Ω

D 2·2 Ω

E 6·4 Ω.

Old Higher 2006 Qu: 9:

9. A battery of e.m.f. 12 V and internal resistance 3·0 Ω is connected in a circuit as shown.



When switch **S** is closed the ammeter reading changes from

A 2·0 A to 1·0 A

B 2·0 A to 2·4 A

C 2·0 A to 10 A

D 4·0 A to 1·3 A

E 4·0 A to 6·0 A.

Paper 2 Examples

Old Higher 2011 Qu: 24:

24. (*a*) A supply of e.m.f. 10·0 V and internal resistance *r* is connected in shown in Figure 1.

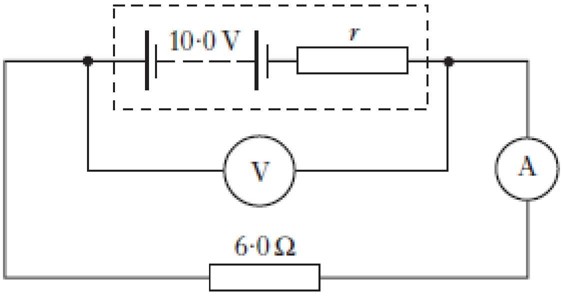


Figure 1

The meters display the following readings.

Reading on ammeter = 1·25 A

Reading on voltmeter = 7·50 V

(i) What is meant by an *e.m.f. of 10·0 V*?

(ii) Show that the internal resistance, *r*, of the supply is 2·0 Ω.

(*b*) A resistor R is connected to the circuit as shown in Figure 2.

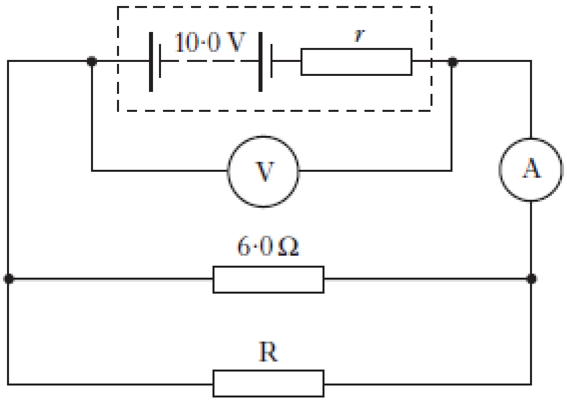


Figure 2

The meters now display the following readings.

Reading on ammeter = 2·0 A

Reading on voltmeter = 6·0 V

(i) Explain why the reading on the voltmeter has decreased.

(ii) Calculate the resistance of resistor R.

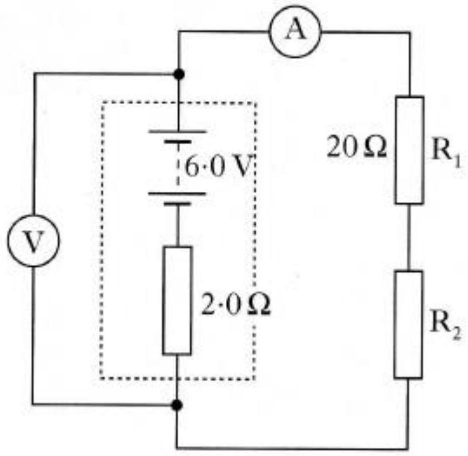
Old Higher 2002 Qu: 24:

24. A battery has an e.m.f. of 6·0 V and internal resistance of 2·0 Ω.

(*a*) What is meant by an *e.m.f. of 6·0 V*?

(*b*) The battery is connected in series with two resistors, R_1 and R_2. Resistor R_1 has a resistance of 20 Ω.

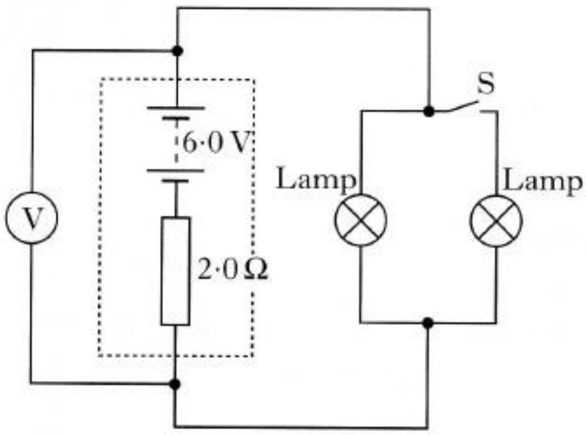
The reading on the ammeter is 200 mA.



(i) Show by calculation that R_2 has a resistance of 8·0 Ω.

(ii) Calculate the reading on the voltmeter.

(*c*) The battery is now connected to two identical lamps as shown below.

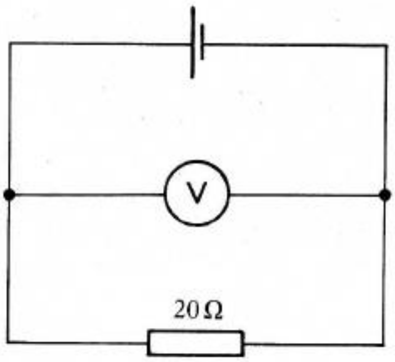


Describe and explain what happens to the reading on the voltmeter when switch S is closed.

Internal resistance homework **Due date:________________**

1.

The reading on the high resistance voltmeter in the circuit shown below is 1·0 V.



The e.m.f. of the cell is 1·5 V.
The internal resistance of the cell is

A 0·1 Ω

B 0·5 Ω

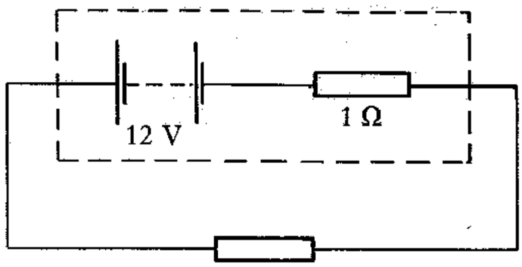
C 1·0 Ω

D 2·5 Ω

E 10 Ω.

2.

A battery of e.m.f. 12 V and internal resistance 1 Ω is connected across a 2 Ω resistor, as shown in the circuit below.

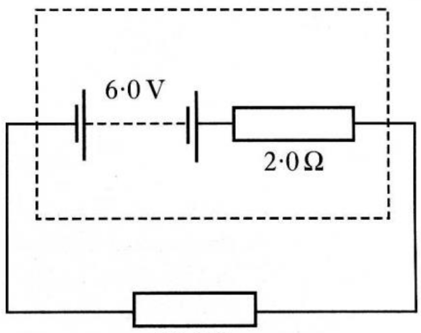


Which row in the following table shows the correct values for current, terminal potential difference and lost volts in this circuit?

	Current/A	*t.p.d./V*	*lost volts/V*
A	4	4	8
B	4	8	4
C	6	4	8
D	6	8	4
E	12	8	4

3.

A battery has an e.m.f. of 6·0 V and an internal resistance of 2·0 Ω. It is connected to a 10·0 Ω resistor, as shown below.



The p.d. across the 10·0 Ω resistor is

A 1·0 V

B 1·2 V

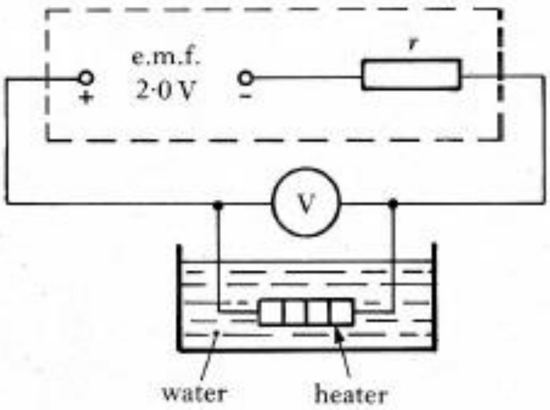
C 4·8 V

D 5·0 V

E 6·0 V.

4.

A heater of resistance 0·32 ohms is connected to a power supply of e.m.f. 2·0 volts and internal resistance r as shown below.



(*a*) State what is meant by the term electromotive force (e.m.f.).

(*b*) The power output of the **heater** is 8·0 watts.

Calculate:

(i) the current in the heater;

(ii) the reading on the voltmeter;

(iii) the internal resistance of the power supply.

(*c*) Another identical heater is now placed in the water and connected in parallel with the original heater.

The rest of the circuit is unaltered.

How does this affect the rate at which heat is supplied to the water?

Justify your answer by calculation.

4. Internal Resistance & EMF from a graph:

Learning outcomes:

- Determining internal resistance and electromotive force using graphical analysis.

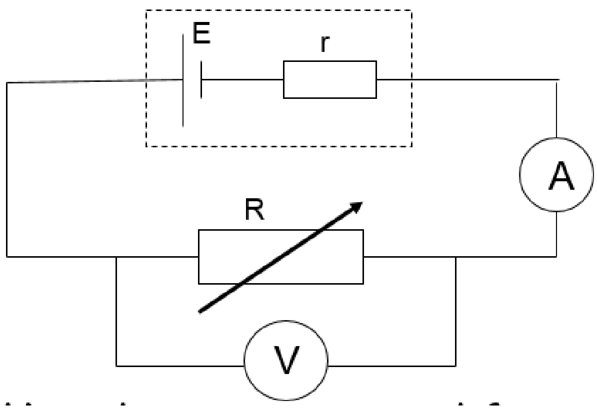
Finding Internal Resistance (r) Experimentally:

The e.m.f. and internal resistance of a cell can be found using the circuit below:

V (the t.p.d.) and I are measured

for various values of the variable resistor.

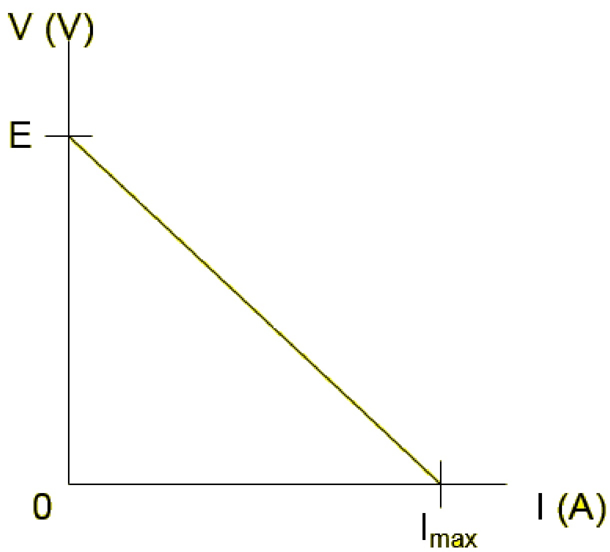
A table is compiled and then a graph of voltage against current is plotted.



Results:

Current (A)	t.p.d. across the resistor (V)

The following graph is obtained (using line of best fit):



There are two key pieces of information provided by the graph:

1. The internal resistance, r.

This is equal to the negative of the gradient of the line.

r = - gradient of the line

2. The E.m.f, E. This is equal to the y intercept.

E = intercept on y-axis.

What is the short circuit current?:

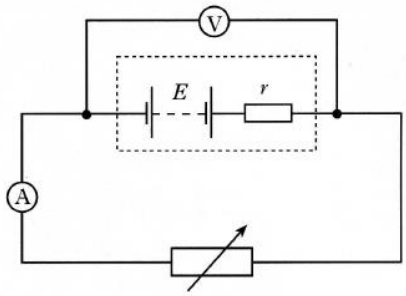
This is the current produced the E.m.f. and the internal resistor ONLY (i.e. the load resistor is not taken into account). You can calculate by:

Short circuit current $I = \frac{E}{r}$

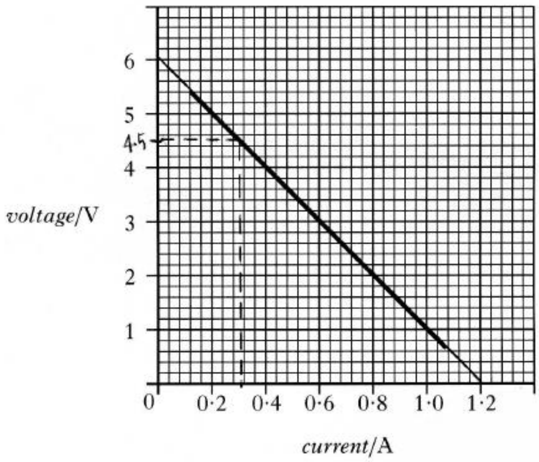
Paper 2 Examples:

Old Higher 2005 Qu: 25:

25. A student sets up the following circuit to find the e.m.f. *E* and the internal resistance *r* of a battery.



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



(*a*) What is meant by the term *e.m.f.*?

(*b*) (i) Use the graph to determine:

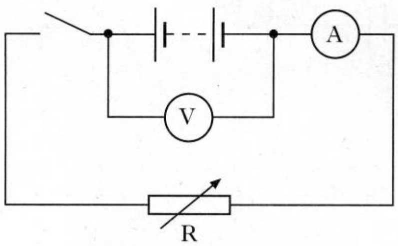
(A) the e.m.f.;

(B) the internal resistance of the battery.

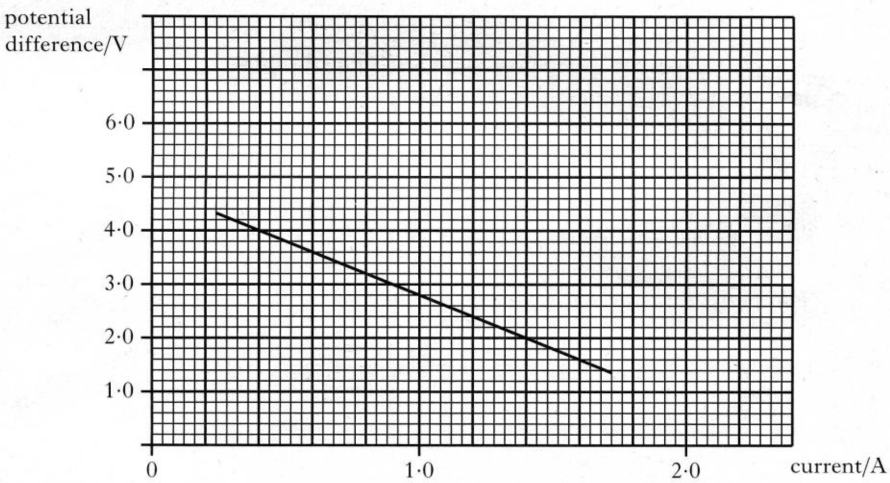
(ii) Show that the variable resistor has a value of 15 Ω when the current is 0·30 A.

Old Higher 2001 Qu: 24:

24. (*a*) The following circuit is used to measure the e.m.f. and the internal resistance of a battery.



Readings of current and potential difference from this circuit are used to produce the following graph.



Use information from the graph to find:

(i) the e.m.f. of the battery, in volts;

(ii) the internal resistance of the battery.

(*b*) A car battery has an e.m.f. of 12 V and an internal resistance of 0·050 Ω.

(i) Calculate the short circuit current for this battery.

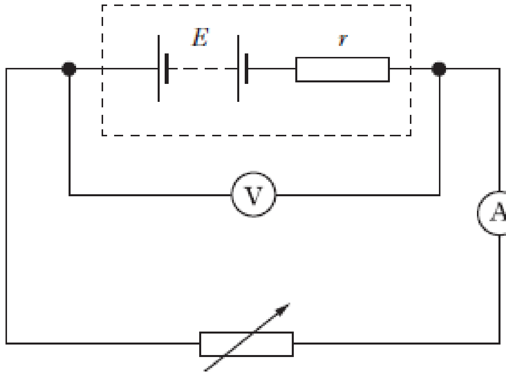
(ii) The battery is now connected in series with a lamp. The resistance of the lamp is 2·5 Ω. Calculate the power dissipated in the lamp.

Old Higher 2014 Qu: 25:

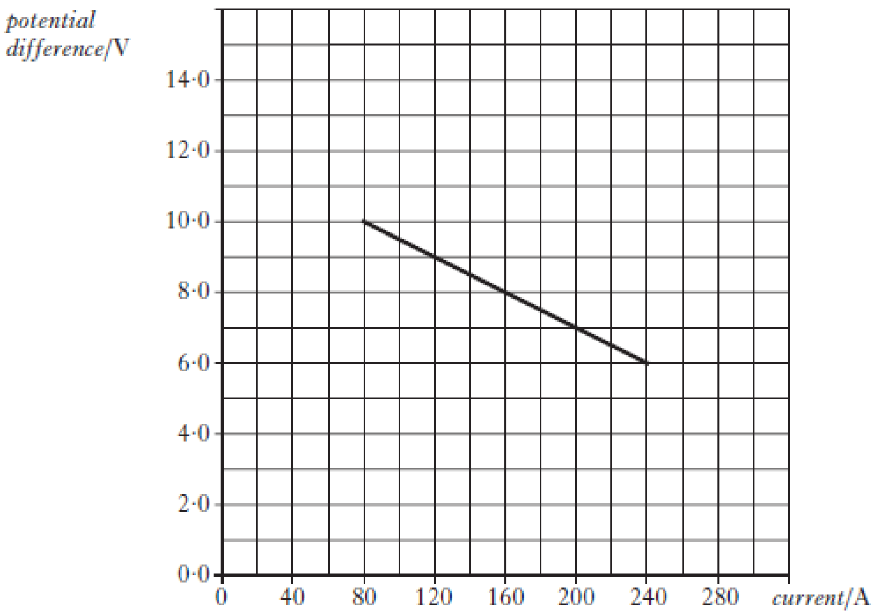
25. A technician is testing a new design of car battery.

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

(*a*) 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.

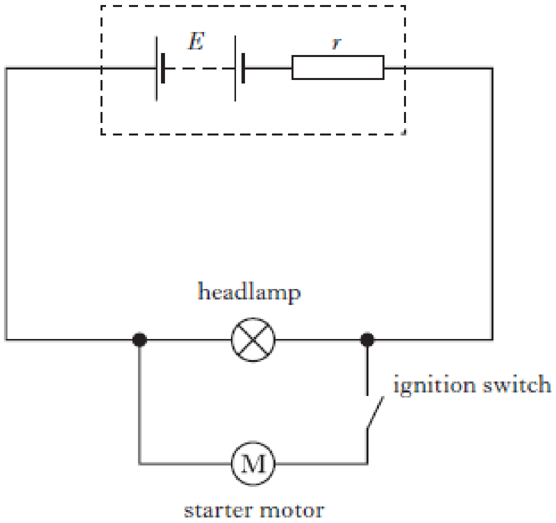
(ii) Calculate the internal resistance of the car battery.

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

Calculate the short circuit current.

25. **(continued)**

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

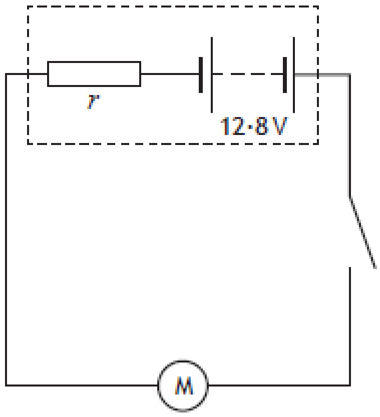


The technician notices that the headlamp becomes dimmer when the ignition switch is closed and the starter motor operates.

Explain why this happens.

CfE Higher 2015 Qu: 10:

10. A car battery is connected to an electric motor as shown.



The electric motor requires a large current to operate.

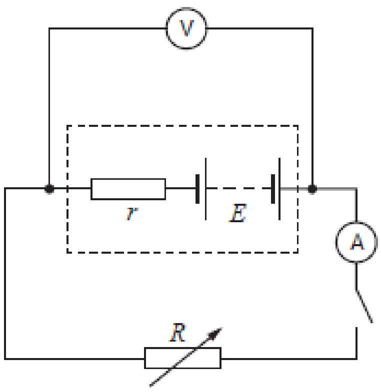
(a) The car battery has an e.m.f. of 12·8 V and an internal resistance r of $6{\cdot}0 \times 10^{-3}\,\Omega$. The motor has a resistance of $0{\cdot}050\,\Omega$.

(i) State what is meant by an *e.m.f. of 12·8 V*. **1**

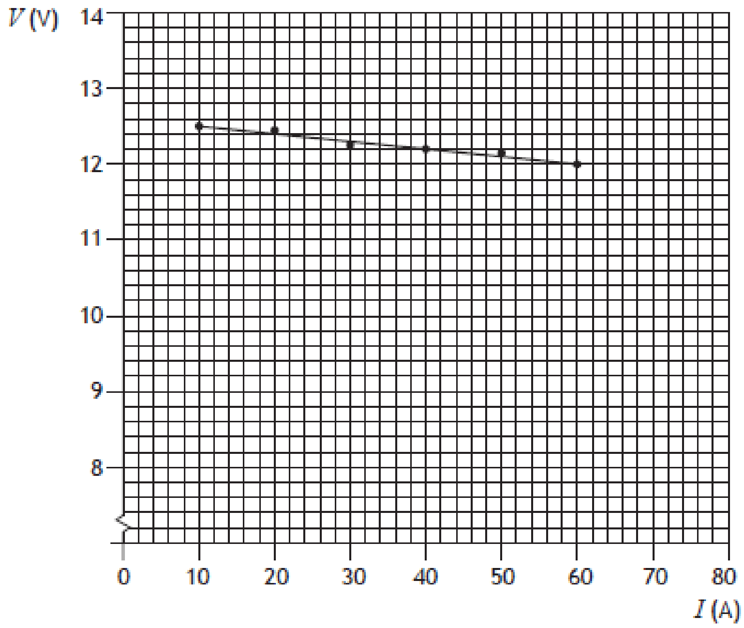
(ii) Calculate the current in the circuit when the motor is operating. **3**

(iii) Suggest why the connecting wires used in this circuit have a large diameter. **1**

(b) A technician sets up the following circuit with a different car battery connected to a variable resistor R.



Readings of current I and terminal potential difference V from this circuit are used to produce the following graph.



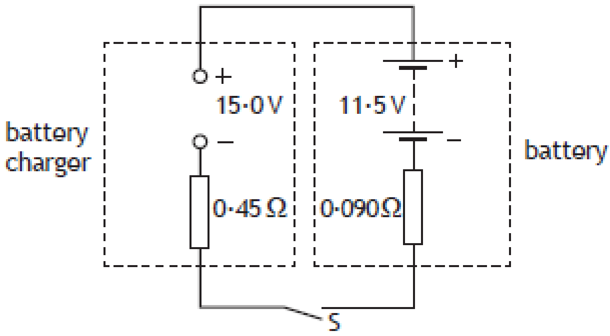
Use information from the graph to determine:

(i) the e.m.f. of the battery; 1

(ii) the internal resistance of the battery; 3

(iii) After being used for some time the e.m.f. of the battery decreases to 11·5 V and the internal resistance increases to 0·090 Ω.

The battery is connected to a battery charger of constant e.m.f. 15·0 V and internal resistance of 0·45 Ω as shown.



(A) Switch S is closed.

Calculate the initial charging current. 3

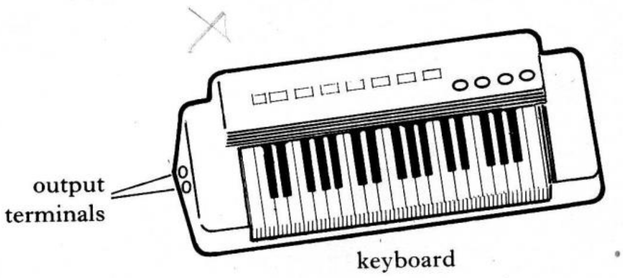
(B) Explain why the charging current decreases as the battery charges. 2

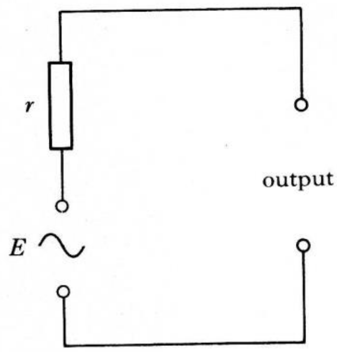
Internal resistance & EMF from a graph homework   Due date:_______________

1.

(*a*) An electronic keyboard contains an audio amplifier with output terminals which can be connected to a loudspeaker.

When a key is pressed, the amplifier may be considered as a source of e.m.f. E and internal resistance r in series, as shown below.

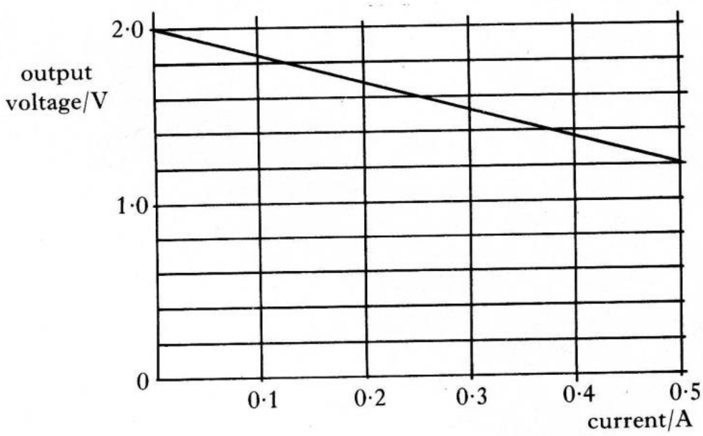




In an experiment to measure the internal resistance of the amplifier, the following equipment is used:

keyboard
a.c. ammeter
a.c. voltmeter
variable resistor.

The graph below displays the results of the experiment.



(i) Describe how the apparatus is used to obtain the data for this graph. Your answer must include a circuit diagram.

(ii) Calculate the value of the internal resistance of the amplifier.

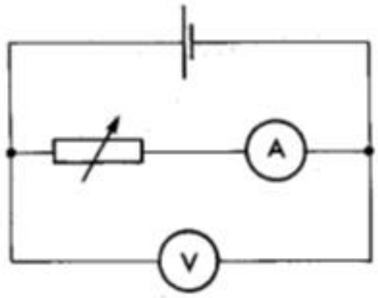
(iii) A loudspeaker of resistance $4{\cdot}0\,\Omega$ is now connected across the output terminals of the amplifier and a key is pressed.

What is the output voltage across the loudspeaker?

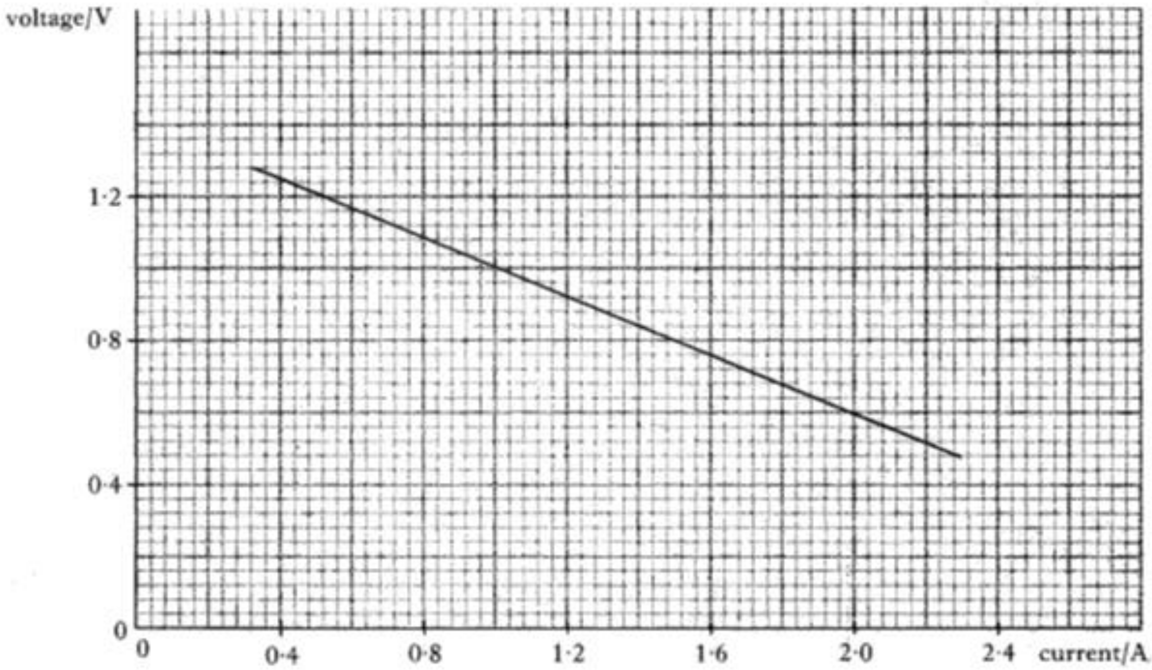
2.

(*b*) (i) State what is meant by the e.m.f. of a cell.

(ii) The circuit shown below is used in an experiment to find the e.m.f. and internal resistance of the rechargeable cell.



The voltmeter and ammeter readings for a range of settings of the variable resistor are used to produce the graph below.



Use the graph to find the values for the e.m.f. **and** internal resistance of the cell.

(*b*) The internal resistance of a power supply can be measured with a voltmeter and a **calibrated** variable resistor.

First, the e.m.f. of the power supply is measured using the voltmeter as shown in Figure 1.

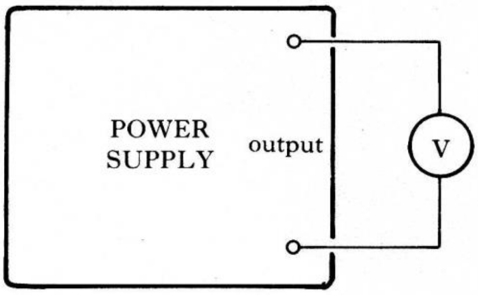


Figure 1

The variable resistor is then connected, as in Figure 2, and adjusted until the output p.d. is equal to half the e.m.f.

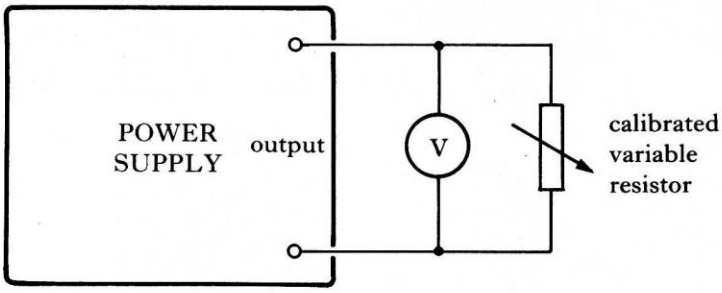


Figure 2

Explain how these measurements can be used to obtain the value of the internal resistance of the power supply. **2**

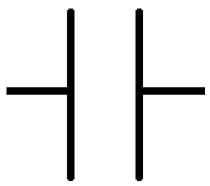
5. Capacitance

Learning outcomes:

- Capacitors and the relationship between capacitance, charge and potential difference.

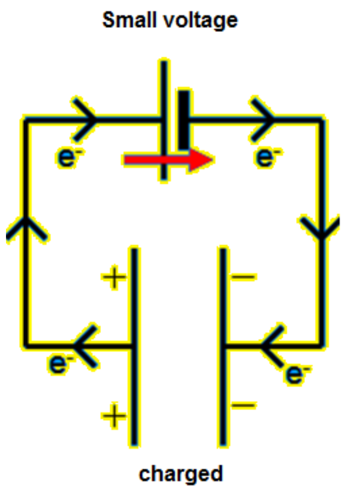
Capacitors:

Circuit symbol:



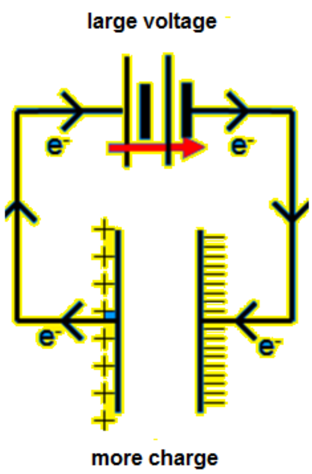
- CAPACITORS are devices which can store charge. The ability of a device to store charge is called its capacitance.
- A capacitor is two conducting layers separated by an insulator.

Storing charge:



- Charge can be stored on parallel metal plates by connecting them to a **d.c. source**.
- Electrons leave one plate and at the same time electrons are added to the other plate.
- The **energy** to cause this transfer of charge from one plate to the other is the **work done** by the source.

What effect does a larger supply voltage have?

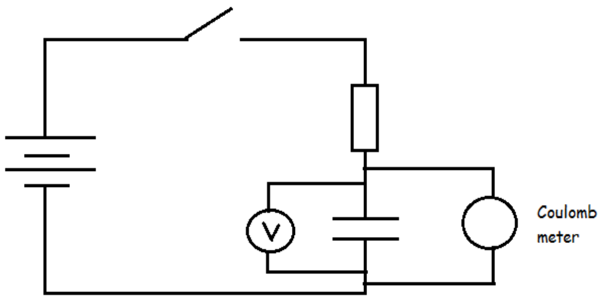


- The plates build up charge until the p.d. across the plates is **equal** to the p.d. of the source.
- Therefore, a larger supply voltage = larger charge
- The charge (Q) on two parallel conducting plates is **directly proportional** to the p.d. (V) between the plates.

$$Q \propto V$$

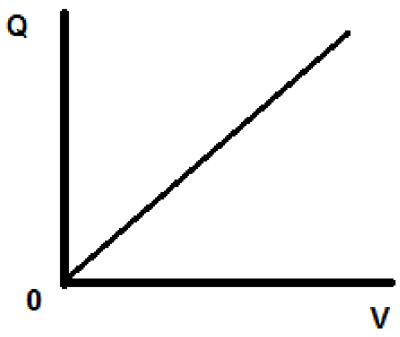
- The parallel plates **store the energy** supplied to them in an electric field between the plates.
- When the source is disconnected, the **charge and energy are stored**.

Experimentally investigating charge on and p.d. across the plates of a capacitor:



- Discharge the capacitor (there is a button beside the capacitor).
- Connect the circuit and set the switch to charge the capacitor as shown in the diagram.
- Allow enough time for the capacitor to charge fully.
- Set the switch to fully discharge the capacitor through the coulomb meter.
- Repeat for other charging voltages. Plot a graph of charge against voltage.

Results:



The charge, Q, is directly proportional to the voltage, V.

$$Q = CV$$

Capacitance equation:

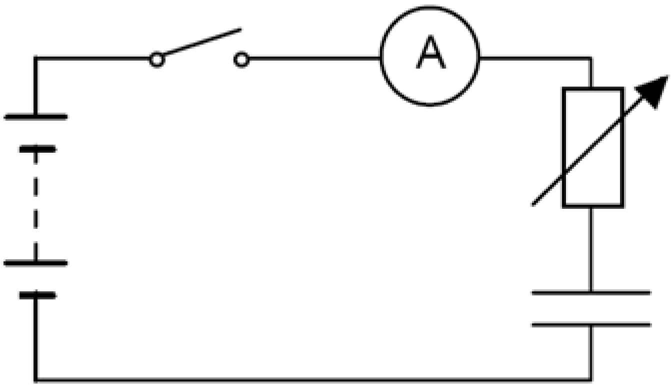
- Capacitance C is the ratio of charge to p.d.
- The unit of capacitance is the Farad, F.
- **One Farad is one Coulomb per Volt.**
-

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

- The Farad is often expressed as μF ($\times 10^{-6}$F), nF ($\times 10^{-9}$F) or pF ($\times 10^{-12}$F)

Worked Example:

Using the circuit below a capacitor is charged at a constant charging current of 2.0×10^{-5} A.



The time taken to charge the capacitor is 30 s and during this time the voltage across the capacitor rises from 0 V to 12 V.
What is the capacitance of the capacitor?

Multiple-choice Examples

Old Higher 2002 Qu: 11:

The unit for capacitance can be written as

A $V\,C^{-1}$

B $C\,V^{-1}$

C $J\,s^{-1}$

D $C\,J^{-1}$

E $J\,C^{-1}$.

Old Higher 2003 Qu: 13:

A farad is a

A volt per ampere

B volt per ohm

C coulomb per volt

D coulomb per second

E joule per coulomb.

Old Higher 2009 Qu: 11:

A $25{\cdot}0\,\mu F$ capacitor is charged until the potential difference across it is 500 V.

The charge stored in the capacitor is

A $5{\cdot}00 \times 10^{-8}$ C

B $2{\cdot}00 \times 10^{-5}$ C

C $1{\cdot}25 \times 10^{-2}$ C

D $1{\cdot}25 \times 10^{4}$ C

E $2{\cdot}00 \times 10^{7}$ C.

Multiple-choice example – CfE 2016 Qu: 20:

20. A $20\,\mu F$ capacitor is connected to a 12 V d.c. supply.

The maximum charge stored on the capacitor is

A $1{\cdot}4 \times 10^{-3}$ C

B $2{\cdot}4 \times 10^{-4}$ C

C $1{\cdot}2 \times 10^{-4}$ C

D $1{\cdot}7 \times 10^{-6}$ C

E $6{\cdot}0 \times 10^{-7}$ C.

6. Energy Stored in a Capacitor

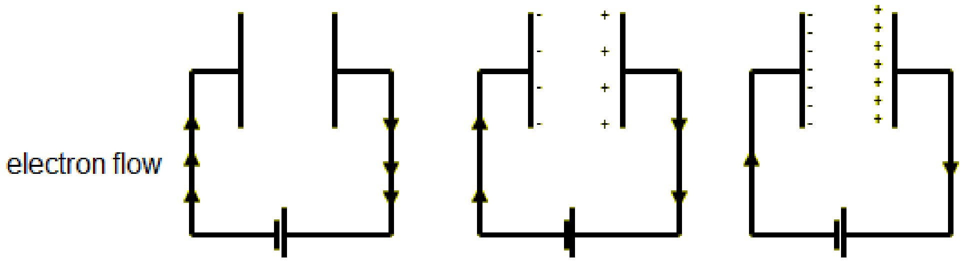
Learning Outcomes:

- The total energy stored in a charged capacitor is the area under the charge against potential difference graph.
- Use the relationships between energy, charge, capacitance and potential difference.
- Variation of current and potential difference against time for both charging and discharging.
- The effect of resistance and capacitance on charging and discharging curves.

Work done in Charging a Capacitor:

- **Work must be done (against the electrostatic forces) when pushing electrons on to the negative plate and pulling them off the positive plate.**

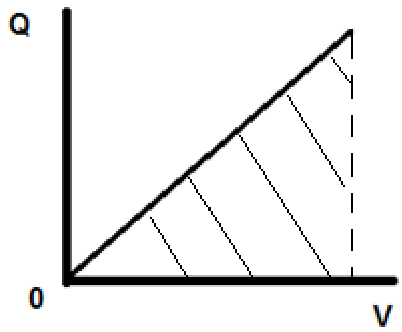
- The negative electrons are pulled away from the positive plate and then pushed onto the negative plate. They both act against their attraction (as negative charges repel other negative charges and are attracted to positive charges).
- This work becomes energy stored in the electric field between the plates and the capacitor.



- Once some charge is on the plate, this will repel more charge and so the **current decreases** until the electrons from the cell do not have enough energy to 'climb' the potential gradient onto the plate.

- The charging then ceases.
- In this way, work is done in charging the capacitor.

- The work done in charging a capacitor is given by the area under the graph of charge against p.d.



- Energy stored in a capacitor = ½ x b x h

  = ½ x charge x p.d.

  = ½ x Q x V

- We already know that Q = CV. There we can write the following three equations:
- **Energy stored in a capacitor,** $E = \frac{1}{2} QV = \frac{1}{2} CV^2 = \frac{\frac{1}{2} Q^2}{C}$
- It is very important that you use the equations above (laid out in this way in the relationship sheet) and **do not use** W = QV (this is used later on in the course).

Summary of main points:

- Work (energy) is required to charge a capacitor to move the electrons onto the plate **against** the force due to the other charges on the plate.
- This energy is found by the area under a QV graph or by any of the equations:
- $E = \frac{1}{2} QV = \frac{1}{2} CV^2 = \frac{1}{2} Q^2/C$

Exam hint 1:

- They will often give you the voltage of the resistor and then question you about the capacitor.
- Remember you must first calculate the voltage of the capacitor (use the voltage in series rule):

$$V_s = V_1 + V_2$$

$$V_s = V_R + V_C$$

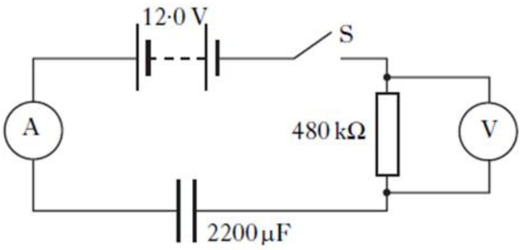
Exam hint 2:

- The initial charging current is the current right at the start of the charging process.
- We can see from our QV graph, that the voltage across the capacitor right at the start is 0 V.
- This means all the voltage is in the resistor
- We can therefore use V = IR to work out the initial charging current because all the voltage in the resistor at the start.
- See example 1 (a)

Paper 2 Examples

Old Higher 2007 Qu: 26:

26. An uncharged 2200 μF capacitor is connected in a circuit as shown.



The battery has negligible internal resistance.

(*a*) Switch S is closed. Calculate the initial charging current.

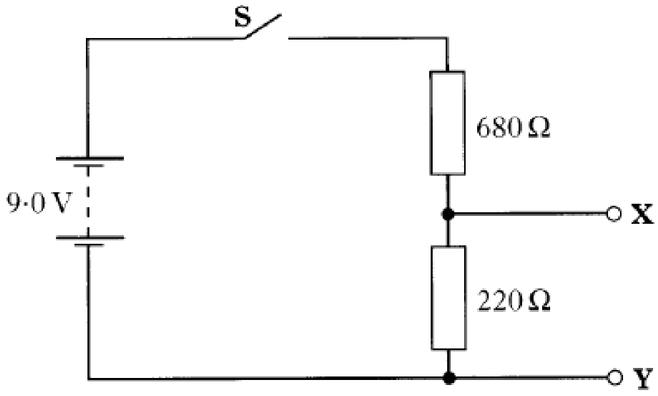
(*b*) At one instant during the charging process the potential difference **across the resistor** is 3·8 V.

Calculate the charge stored in the capacitor at this instant.

(*c*) Calculate the **maximum** energy the capacitor stores in this circuit.

Old Higher 2006 Qu: 25:

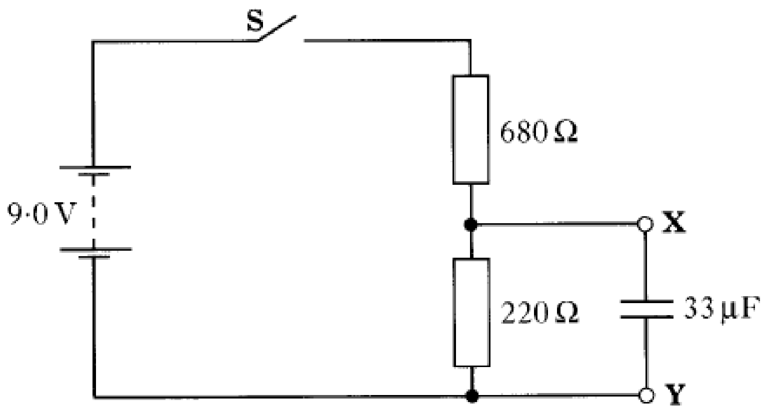
25. The 9·0 V battery in the circuit shown below has negligible internal resistance.



(*a*) Switch **S** is closed.
Calculate the potential difference between **X** and **Y**.

(*b*) Switch **S** is opened.

An uncharged 33 μF capacitor is connected between **X** and **Y** as shown.



Switch **S** is then closed.

(i) Explain why work is done in charging the capacitor.

(ii) State the value of the maximum potential difference across the capacitor in this circuit.

(iii) Calculate the maximum energy stored in the capacitor.

7. Charge and Discharge Graphs

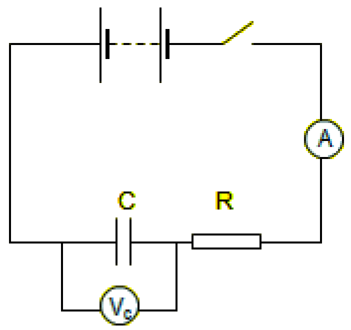
Learning Outcomes:

- Variation of current and potential difference against time for both charging and discharging.
- The effect of resistance and capacitance on charging and discharging curves.

Capacitance - Charging / Discharging Graphs – The RC Circuit:

The diagram below shows a d.c. circuit containing a resistor and capacitor in series.

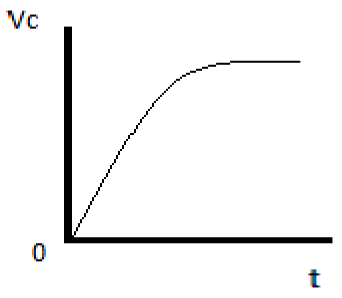
This is known as an RC circuit, or a CR circuit.



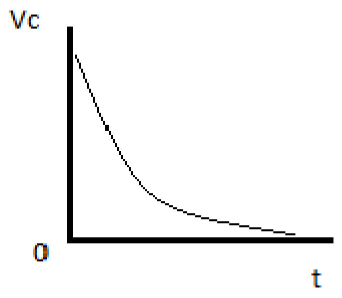
As we have previously seen, a capacitor does not instantly charge. It takes some time to fully charge as the electrons move against the forces of repulsion. We can therefore investigate how both voltage and current vary with time for a charging and a discharging capacitor.

Voltage / time graphs:

Results for **CHARGING** capacitor



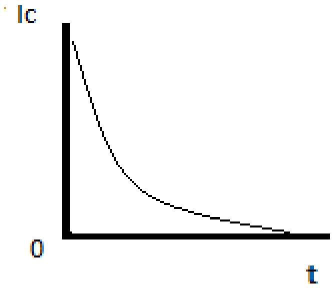
Results for **DISCHARGING** capacitor



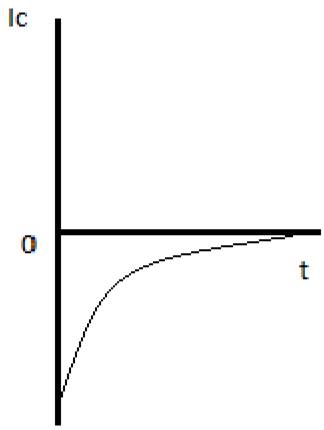
Current / time graphs:

The current during charging and discharging can be displayed by monitoring the potential difference (voltage) across the fixed resistor, R, using the equation I = V / R.

Results for **CHARGING** capacitor



Results for **DISCHARGING** capacitor



Note the negative value for current for the DISCHARGING graph. This is because the direction of the current has changed.

How can the time take to CHARGE / DISCHARGE be affected?

Two adjustments that can be made to an RC circuit to **increase the charging time** are:

1. **Increase the capacitance** (more charge is stored)
2. **Increase the resistance** (less current will flow at the start)

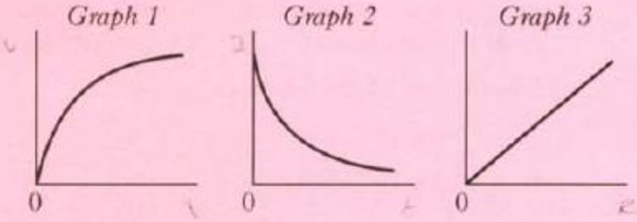
Increasing the supply voltage can also increase the time taken to charge.

Multiple-choice Examples

Old Higher 2006 Qu: 11:

11. A student carries out three experiments to investigate the charging of a capacitor using a d.c. supply.

The graphs obtained from the experiments are shown.



The axes of the graphs have not been labelled.

Which row in the table shows the labels for the axes of the graphs?

	Graph 1	*Graph 2*	*Graph 3*
A	voltage and time	current and time	charge and voltage
B	current and time	voltage and time	charge and voltage
C	current and time	charge and voltage	voltage and time
D	charge and voltage	current and time	voltage and time
E	voltage and time	charge and voltage	current and time

Old Higher 2011 Qu: 13:

13. In an experiment to find the capacitance of a capacitor, a student makes the following measurements.

potential difference across capacitor = (10·0 ± 0·1) V

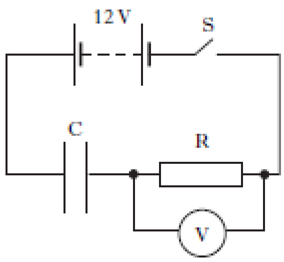
charge stored by capacitor = (500 ± 25) μC

Which row in the table gives the capacitance of the capacitor and the percentage uncertainty in the capacitance?

	Capacitance/μF	*Percentage uncertainty*
A	0·02	1
B	0·02	5
C	50	1
D	50	5
E	5000	6

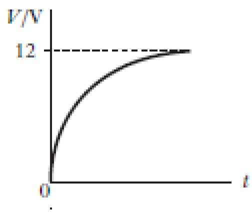
Old Higher 2010 Qu: 12:

12. A circuit is set up as shown.

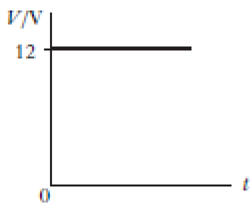


The capacitor is initially uncharged. Switch S is now closed. Which graph shows how the potential difference, V, across R, varies with time, t?

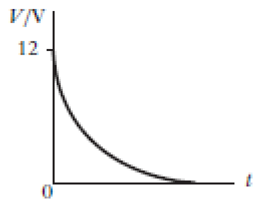
A



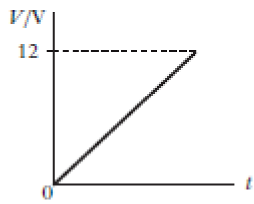
B



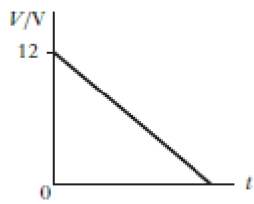
C



D



E



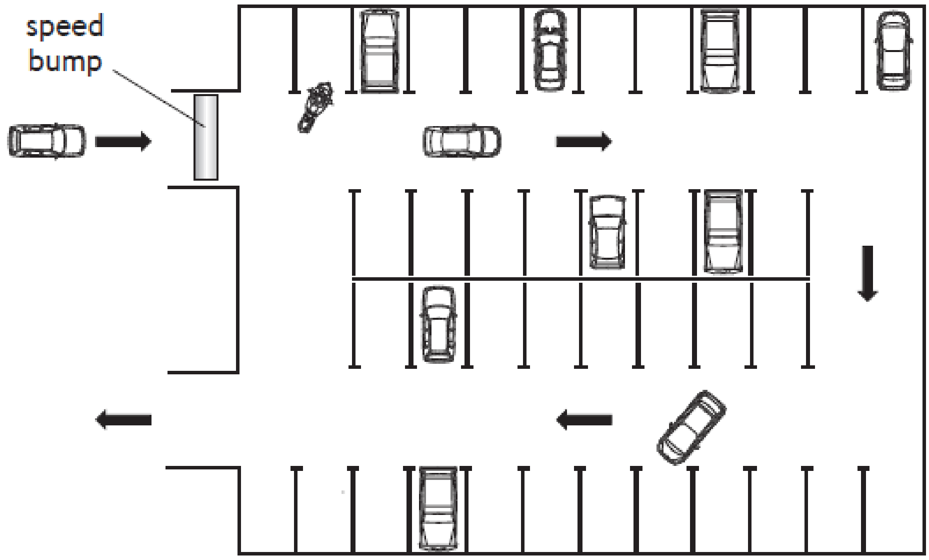
Paper 2 Examples

Open-ended question – CfE 2019:

13. (continued)

(d) The use of analogies from everyday life can help improve the understanding of physics concepts.

Vehicles using a car park may be taken as an analogy for the charging of a capacitor.



Use your knowledge of physics to comment on this analogy. **3**

Old Higher 2010 Qu: 24:

24. An experiment is carried out to measure the time taken for a steel ball to fall vertically through a fixed distance using an electronic timer.

(*a*) The experiment is repeated and the following values for time recorded.

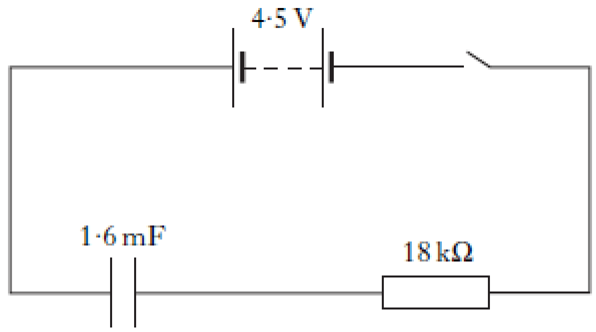
0·49 s, 0·53 s, 0·50 s, 0·50 s, 0·55 s, 0·51 s.

Calculate:

(i) the mean value of the time;

(ii) the approximate random uncertainty in the mean value of the time.

(*b*) Part of the circuit in the electronic timer consists of a 1·6 mF capacitor and an 18 kΩ resistor connected to a switch and a 4·5 V supply.



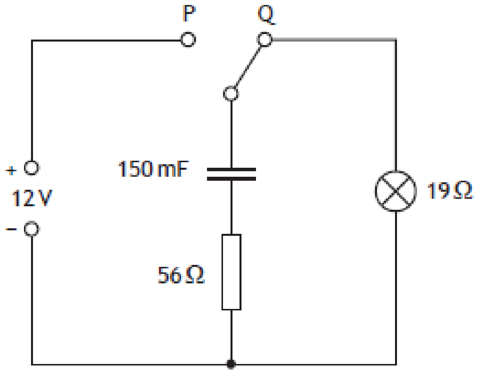
(i) Calculate the charge on the capacitor when it is fully charged.

(ii) Sketch the graph of the current in the resistor against time as the capacitor charges.

Numerical values are required on the current axis.

CfE Higher 2016 Qu: 13:

13. A technician sets up a circuit as shown.



The power supply has negligible internal resistance.

(a) The capacitor is initially uncharged.

The switch is moved to position P and the capacitor charges.

(i) State the potential difference across the capacitor when it is fully charged. **1**

(ii) Calculate the maximum energy stored by the capacitor. **3**

(b) The switch is now moved back to position Q.

Determine the maximum discharge current in the circuit. **3**

(c) The technician replaces the 150 mF capacitor with a capacitor of capacitance 47 mF.

The switch is moved to position P and the capacitor is fully charged.

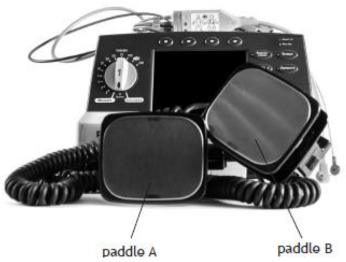
The switch is now moved to position Q.

State the effect that this change has on the time the lamp stays lit.

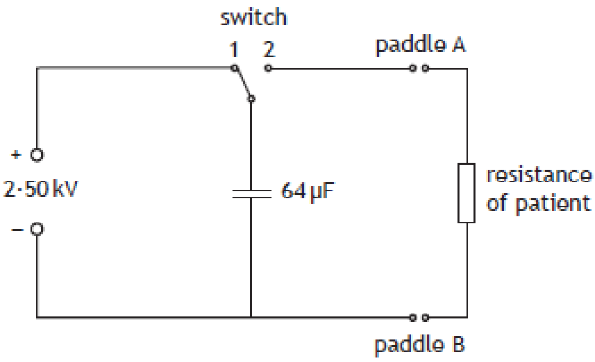
You must justify your answer. **2**

CfE Higher 2015 Qu: 11:

11. A defibrillator is a device that provides a high energy electrical impulse to correct abnormal heart beats.



The diagram shows a simplified version of a defibrillator circuit.



The switch is set to position 1 and the capacitor charges.

(a) Show the charge on the capacitor when it is fully charged is 0·16 C. 2

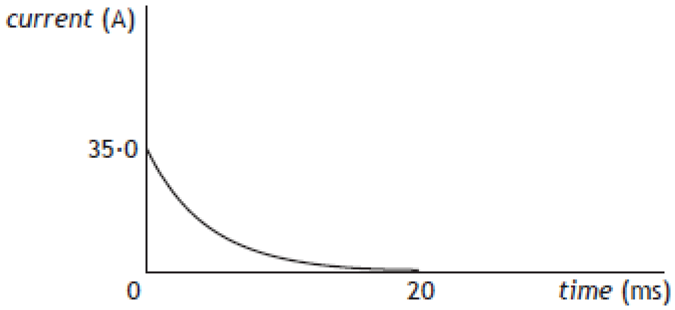
(b) Calculate the maximum energy stored by the capacitor. 3

(c) To provide the electrical impulse required the capacitor is discharged through the person's chest using the paddles as shown

The initial discharge current through the person is 35·0 A.

(i) Calculate the effective resistance of the part of the person's body between the paddles. 3

(ii) The graph shows how the current between the paddles varies with time during the discharge of the capacitor.



The effective resistance of the person remains the same during this time.

Explain why the current decreases with time. 1

(iii) The defibrillator is used on a different person with larger effective resistance. The capacitor is again charged to 2·50 kV.

On the graph in (c)(ii) add a line to show how the current in this person varies with time.

(An additional graph, if required, can be found on *Page thirty-eight*). 2

Capacitance homework **Due date:**

1.

. A capacitor is marked 10 V, 100 μF.

The charge stored in the capacitor when it is used at its rated voltage is

A 1×10^{-5} C

B 1×10^{-3} C

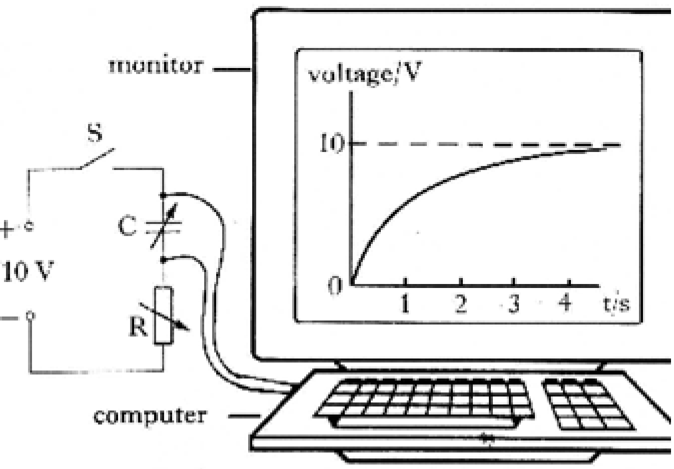
C 5×10^{-3} C

D 1×10^{3} C

E 1×10^{5} C.

2.

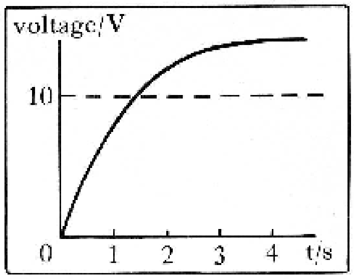
The diagram below shows an experiment in which a computer is used to draw a voltage–time graph for the charging of a capacitor from a supply of e.m.f. 10 V. The supply has negligible internal resistance.



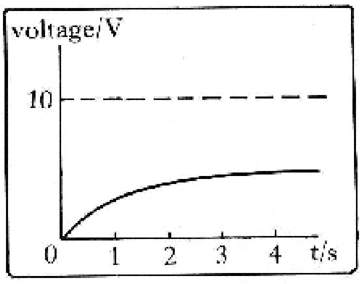
When the switch S is closed, a graph appears on the monitor screen as shown. Switch S is then opened. The capacitor is fully discharged and the values of C and R are both **increased**. Switch S is now closed again.

If no other changes are made, which of the following graphs appears on the monitor screen?

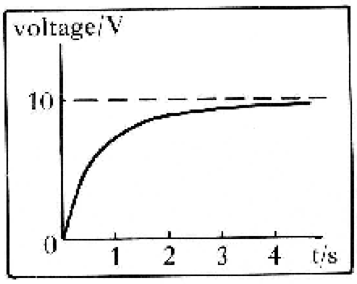
A



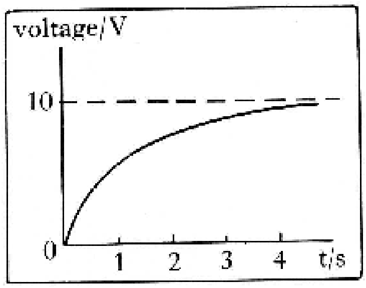
B



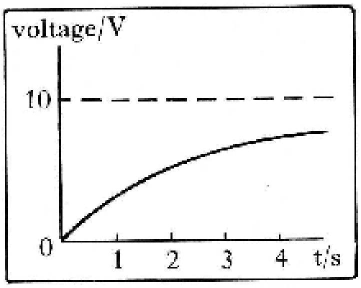
C



D



E



3.

The energy stored in a $500\,\mu\text{F}$ capacitor charged to a voltage of 20 V is

A 5×10^{-3} J

B $2{\cdot}5 \times 10^{-2}$ J

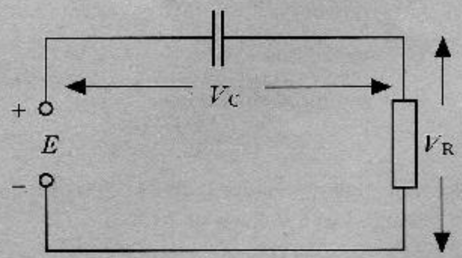
C 5×10^{-2} J

D 1×10^{-1} J

E 2×10^{-1} J.

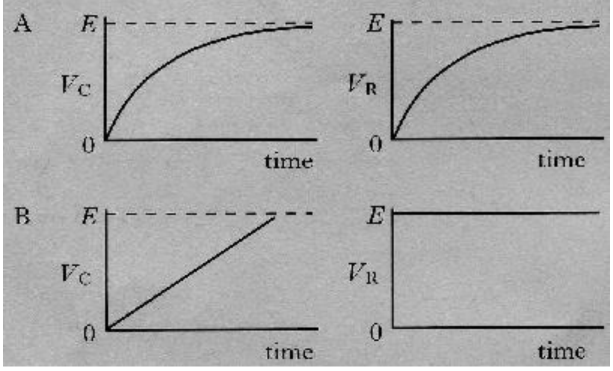
4.

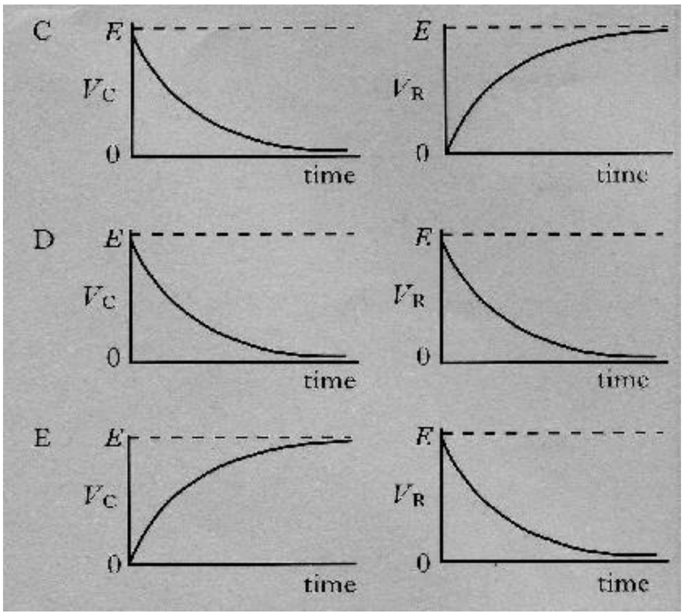
In the following circuit, a capacitor is being charged up from a d.c. source of e.m.f. E. The capacitor has a resistor in series with it, as shown.



The voltages, V_C and V_R, across the components are recorded at regular time intervals as the capacitor charges up.

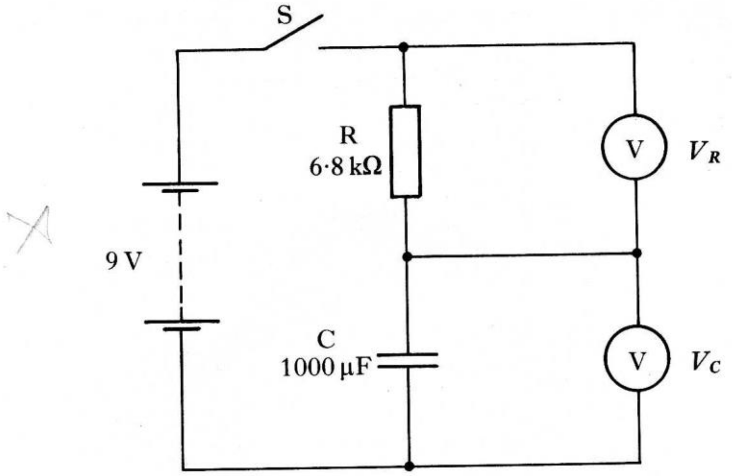
Which of the pairs of graphs shown below correctly represents the voltages across the capacitor and the resistor during charging?





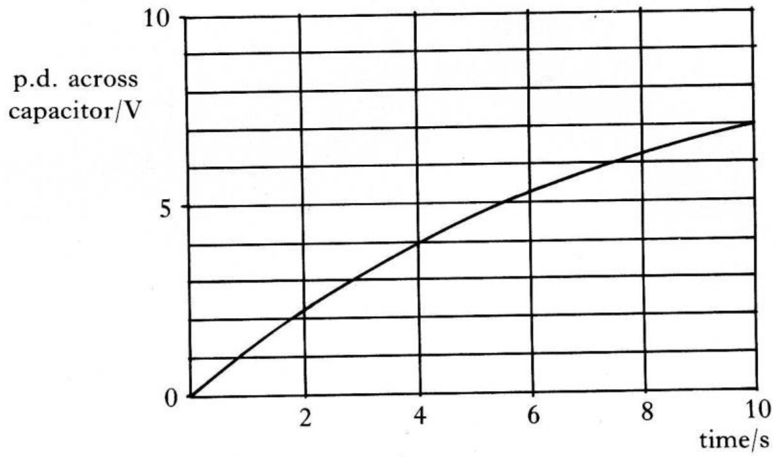
5.

The following circuit is set up to investigate the charging of a capacitor.



At the start of the experiment the capacitor is uncharged.

(*a*) The graph below shows how the p.d. V_C across the capacitor varies with time from the instant the switch S is closed.



Sketch a graph showing how the p.d. V_R across the resistor varies with time during the first 10 s of charging.

(*b*) Calculate the current in the circuit at the instant the p.d. across the capacitor is 6·0 V.

(*c*) (i) When the capacitor is fully charged, it is removed from the circuit and connected across a 10 Ω resistor.

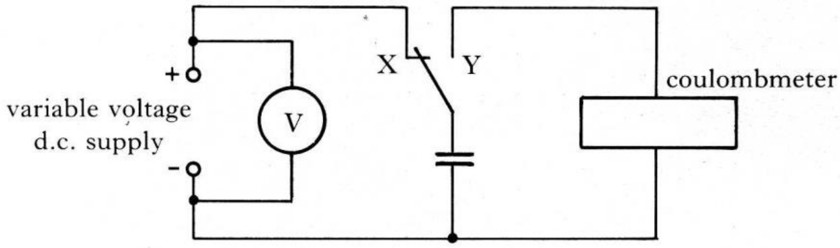
What is the total energy dissipated in the resistor?

(ii) In another experiment, the fully charged capacitor is connected across a 20 Ω resistor instead of the 10 Ω resistor.

How does the energy dissipated in this resistor compare with that calculated in part (i)? You must justify your answer.

6.

(*a*) The circuit shown below is used to find the capacitance of a capacitor.



With the switch in position X, the capacitor charges up to the supply voltage.
The reading on the voltmeter is noted and the switch is moved to position Y.
The coulombmeter then indicates the charge stored by the capacitor.

(i) One set of results is recorded below.

Voltmeter reading = 1·5 V
Coulombmeter reading = 24 μC.

Use these results to calculate a value for the capacitance of the capacitor.

(ii) The experiment is repeated with the **same** capacitor for five different values of the supply voltage, giving the following values for the capacitance.

Capacitance in μF = 16, 18, 20, 16, 15.

Using these five results, calculate the mean value for the capacitance **and** the approximate random error in this value.

(iii) How could the approximate random error in the mean value of the capacitance be reduced?

8. Semiconductors

Learning outcomes:

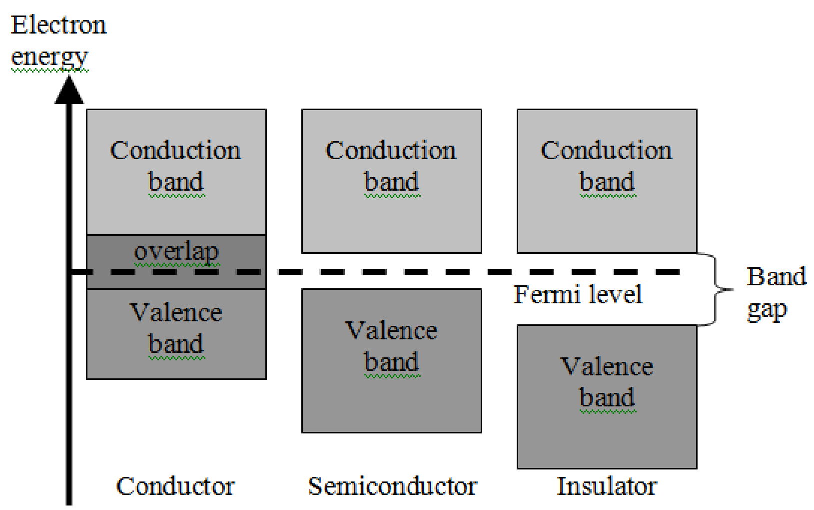
- Solids can be categorised into conductors, semiconductors or insulators by their ability to conduct electricity.
- The electrons in atoms are contained in energy levels. When the atoms come together to form solids, the electrons then become contained in energy bands separated by gaps.
- In metals, the highest occupied band is not completely full and this allows the electrons to move and therefore conduct. This band is known as the conduction band.
- In an insulator, the highest occupied band (called the valence band) is full. The first unfilled band above the valence band is the conduction band. For an insulator, the gap between the valence band and the conduction band is large and at room temperature there is not enough energy available to move electrons from the valence band into the conduction band where they would be able to contribute to conduction. There is no electrical conduction in an insulator.
- In a semiconductor, the gap between the valence band and conduction band is smaller and at room temperature there is sufficient energy available to move some electrons from the valence band into the conduction band allowing some conduction to take place. An increase in temperature increases the conductivity of a semiconductor.

Semiconductors:

- By considering their electrical properties, we can divide materials into three groups:
- Conductors – materials with many free electrons. These electrons can be easily made to flow through the material. For example, all metals, semi-metals like graphite and arsenic.
- Semiconductors – Materials which are insulators when pure, but will conduct by the addition of impurities, e.g. silicon (Si), germanium (Ge).
- Insulators – Materials that have very few free electrons, which cannot move easily. For example plastic, glass and wood.

Band theory:

The conduction of these three materials can be explained using band theory.



Conductors:

- In metals, the highest occupied band is **not completely full** and this allows the electrons to move and therefore conduct. This band is known as the **conduction band**.

Insulators:

- In an insulator, the highest occupied band (called the **valence band**) is **full**.
- The first unfilled band above the valence band is the conduction band.
- For an insulator, the gap between the valence band and the conduction band is **large** and at **room temperature** there is not enough energy available to move electrons from the valence band into the conduction band where they would be able to contribute to conduction.
- There is no electrical conduction in an insulator.

Semiconductors:

- In a semiconductor, the gap between the valence band and conduction band is **smaller** and at **room temperature** there **is sufficient energy** available to move some electrons from the **valence band** into the **conduction band** allowing some conduction to take place.
- An increase in temperature increases the conductivity of a semiconductor by giving more electrons the energy to move into the conduction band. Therefore reducing its resistance.

(It gives more energy to move electrons from the valence band to the conduction band).

Multiple-choice Examples

Revised Higher Specimen paper Qu: 14:

14. In a semiconductor, the energy gap between the valence band and the conduction band is

A small, allowing some conduction to take place at room temperature

B large, allowing some conduction to take place at room temperature

C zero, allowing electrons to move freely

D large, meaning that no conduction can take place at room temperature

E small, meaning that no conduction can take place at room temperature.

Revised Higher 2012 Qu: 18:

18. The letters **X**, **Y** and **Z** represent missing words from the following passage.

Solids can be divided into 3 broad categories: conductors, insulators and semiconductors.

*In ...***X***... the conduction band is not completely full and this allows electrons to move easily.*

*In ...***Y***... the valence band is full.*

*In ...***Z***... electrons can move from the valence to the conduction band at room temperature.*

Which row in the table shows the missing words?

	X	Y	Z
A	conductors	insulators	semiconductors
B	semiconductors	insulators	conductors
C	insulators	semiconductors	conductors
D	conductors	semiconductors	insulators
E	insulators	conductors	semiconductors

Paper 2 Examples

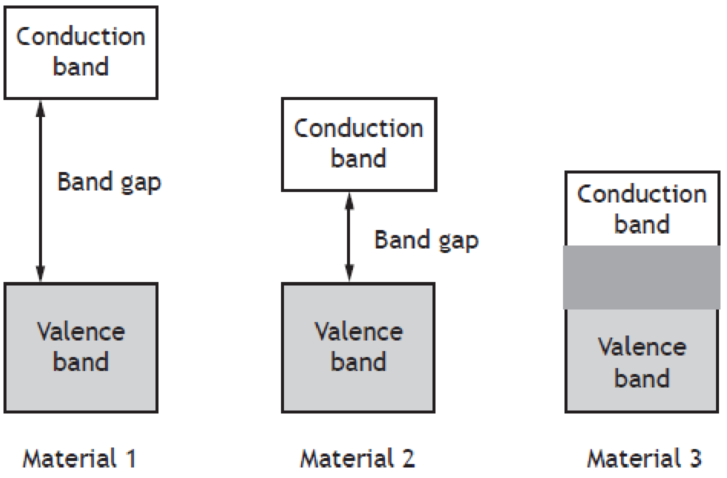
CfE Higher Specimen paper Qu: 14:

The electrical conductivity of solids can be explained by band theory.

The diagrams below show the distributions of the valence and conduction bands of materials classified as *conductors*, *insulators* and *semiconductors*.

Shaded areas represent bands occupied by electrons.

The band gap is also indicated.



(a) State which material is a semiconductor. 1

(b) A sample of pure semiconductor is heated. Use band theory to explain what happens to the resistance of the sample as it is heated. 2

Revised Higher 2013 Qu: 31(a):

31. (*a*) Use band theory to explain how electrical conduction takes place in a pure semiconductor such as silicon.

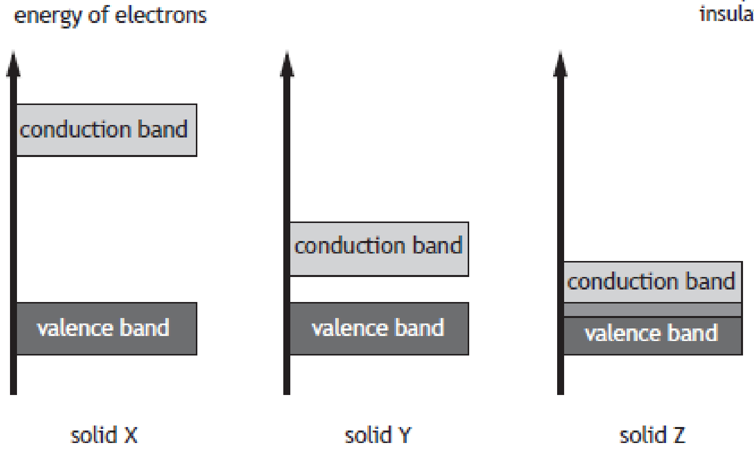
Your explanation should include the terms: *electrons*, *valence band* and *conduction band*. **2**

CfE Higher 2019 Qu: 14:

14. Solids can be categorised as conductors, insulators or semiconductors depending on their ability to conduct electricity. Their electrical conductivity can be explained using band theory.

The diagrams show the valence and conduction bands of three solids X, Y and Z.

One represents a conductor, one represents an insulator and one represents a semiconductor.



(a) Complete the table to show which solid represents a conductor, an insulator and a semiconductor. **1**

Solid	Category
X	
Y	
Z	

(b) Using band theory, explain why conduction can take place in a semiconductor at room temperature. **2**

(c) Silicon can be doped with arsenic to produce an n-type semiconductor.

State the effect that doping has on the conductivity of silicon. **1**

9. p-n Junctions

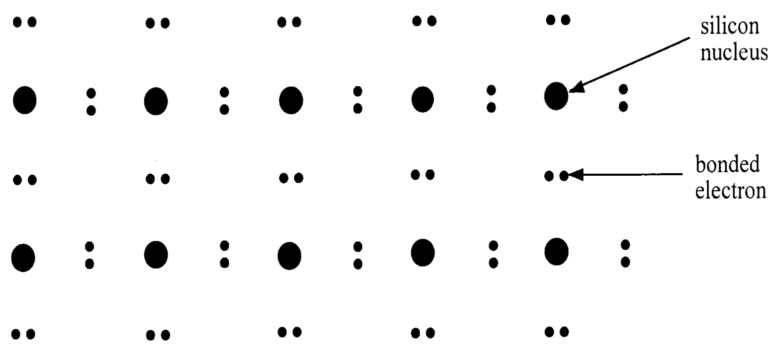
Learning outcomes:

- During manufacture, the conductivity of semiconductors can be controlled, resulting in two types: p-type and n-type.
- 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.
- Solar cells are p-n junctions designed so that a potential difference is produced when photons enter the layer. This is the photovoltaic effect.
- LEDs are p-n junctions which emit photons when a current is passed through the junction.

Doping:

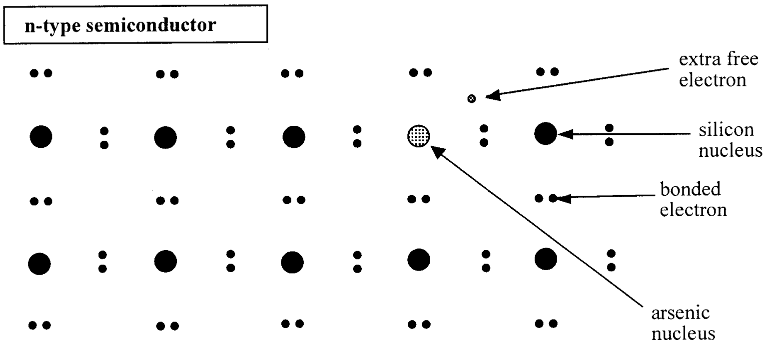
- When we add impurities to a pure semiconductor this is called **Doping.**
- **Doping** reduces the resistance of a semiconductor (therefore making it more conductive to electrical current)

Semiconductors – Silicon:



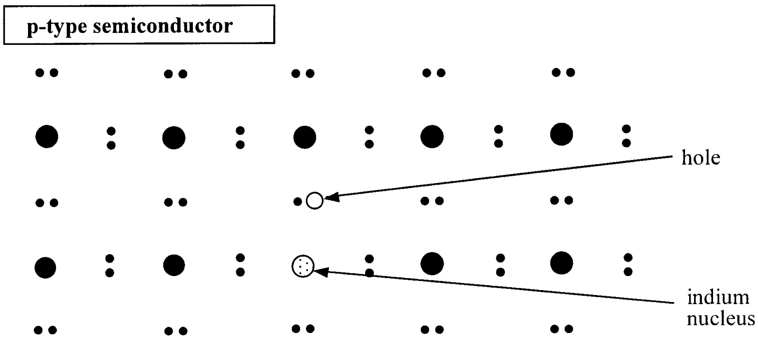
- The silicon atom has 4 valence electrons in the outer shell (this just means they have 4 electrons available for bonding).
- In a pure crystal. Each atom is bonded to another atom, meaning there are very few free electrons.
- The material insulates.
- At higher temperatures, a few electrons escape from their atoms.
- They leave behind a 'hole'.
- Both electrons and holes increase conductivity and reduce resistance.

N-type semiconductor:



- Arsenic is an impurity with five outer electrons.
- If it is added to the silicon, it leaves one spare electron.
- These free electrons can form a current.
- Since the overall charge is negative we call these 'n-type' semiconductors

P-type semiconductor:



- Indium is an impurity with three outer electrons.
- If it is added to the silicon, it leaves a 'hole' i.e. a missing electron
- This hole can move through the lattice, carrying a positive charge.
- This is called a **p-type semiconductor.**

P-type and N-type:

- Both p-type and n-type materials are electrically neutral (only their charges have a charge when an impurity is added).
- The more doping that takes place the more charge carriers there are:
- p-type – majority charge carrier are holes
- n-type – majority charge carrier are electrons

Multiple-choice Examples

Old Higher 2009 Qu: 17:

17. 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?

A I only

B II only

C I and II only

D I and III only

E I, II and III

Old Higher 2004 Qu: 17:

17. Materials are "doped" to produce n-type semiconductor material.

In n-type semiconductor material

A the majority charge carriers are electrons

B the majority charge carriers are neutrons

C the majority charge carriers are protons

D there are more protons than neutrons

E there are more electrons than neutrons.

Old Higher 2003 Qu: 19:

19. 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

Old Higher 2008 Qu: 18:

18. The letters **X**, **Y** and **Z** represent three missing words from the following passage.

Materials can be divided into three broad categories according to their electrical resistance.

..........**X**.......... *have a very high resistance.*

..........**Y**.......... *have a high resistance in their pure form but when small amounts of certain impurities are added, the resistance decreases.*

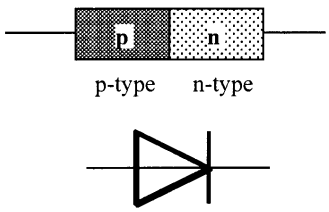
..........**Z**.......... *have a low resistance.*

Which row in the table shows the missing words?

	X	Y	Z
A	conductors	insulators	semi-conductors
B	semi-conductors	insulators	conductors
C	insulators	semi-conductors	conductors
D	conductors	semi-conductors	insulators
E	insulators	conductors	semi-conductors

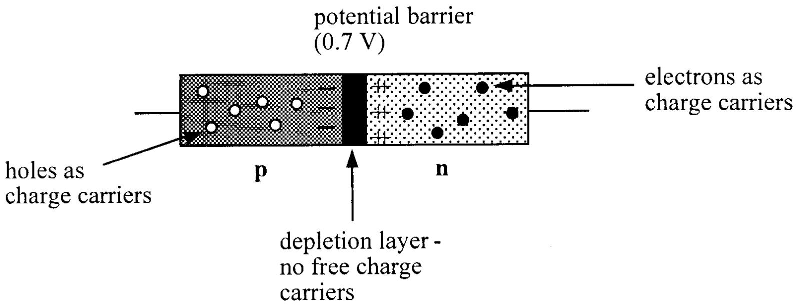
p-n Junctions:

- The p-n junction diode: When a semi-conductor is grown so that one half is p-type and the other is n-type, the resulting product is known as a **p-n junction diode.**



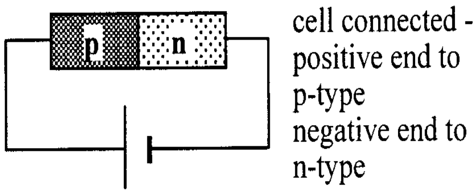
circuit symbol

- Since the electrons and the holes have combined, there are no free charge carriers just around the junction where they join.
- This is called the **depletion layer.**
- There will be a small voltage, a potential barrier, across this junction due to this charge separation.
- This voltage will tend to oppose any further movement of charge.

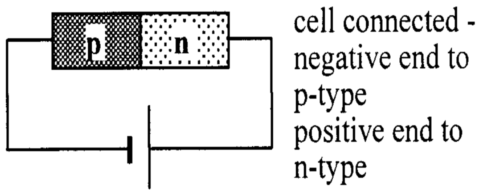


Biasing:

- This is equivalent to having a potential difference across the junction which opposes any further movement of electrons (from n-type to p-type) and holes (from p-type to n-type).
- Applying a voltage to a semiconductor is called **biasing.**
- There are two ways to apply the voltage:



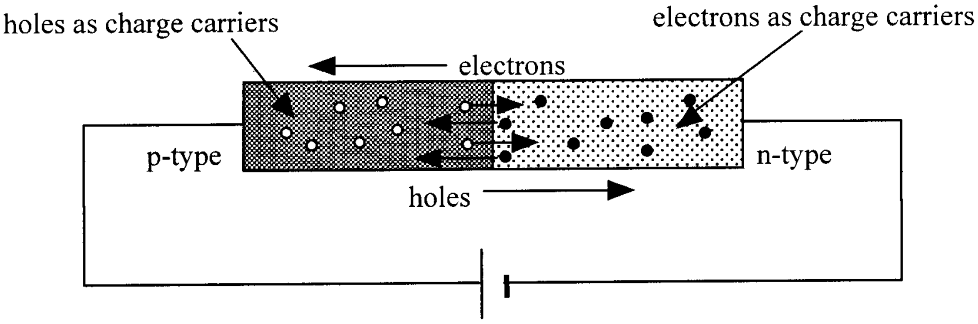
Forward-biased



Reverse-biased

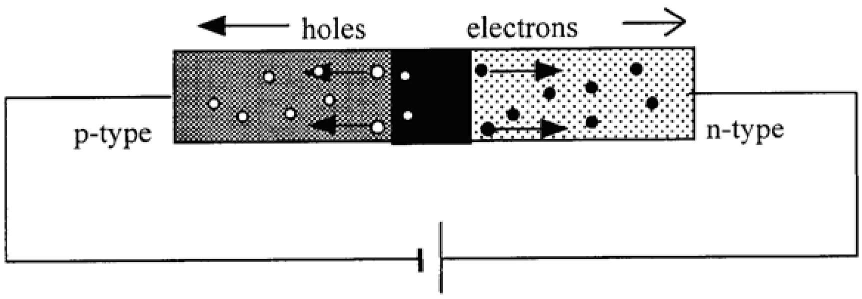
The forward-biased diode:

- In the forward biased diode, the following occurs:
- The negative electrons are given enough energy to flow through the depletion layer and in an anti-clockwise direction to the +ve end of the battery.
- The +ve holes travel in the opposite direction to the –ve end of the battery.
- The depletion layer becomes removed and the diode conducts.

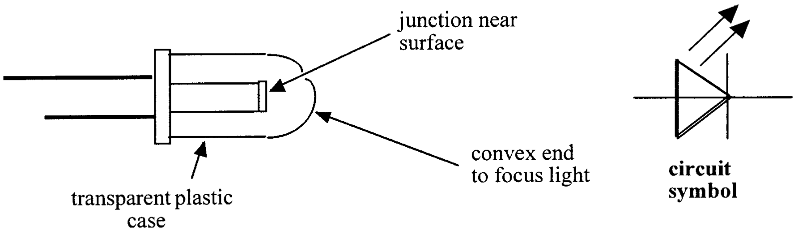


The reverse-biased diode:

- In the reverse-biased diode, the applied potential causes the depletion layer to increase in depth, increasing the size of the potential barrier.
- The diode is now less likely to conduct.



The Light Emitting Diode (LED):

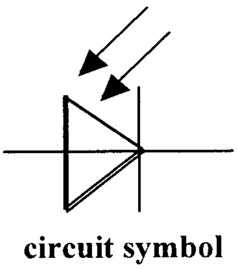


- The LED has a p-n junction very close to the surface.
- It is used in the forward-biased mode.
- When holes and electrons are crossing the junction, some meet, re-combine and emit energy in the form of a photon of light, hence the name.

The photodiode:

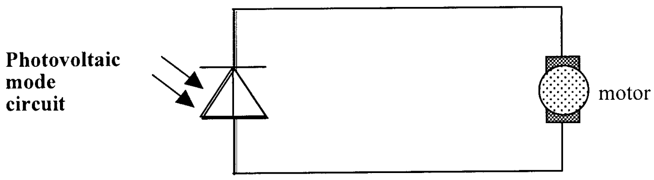
- A p-n junction coated in a transparent coating will **react** to light.
- This photodiode can be used in two modes:

1. Photovoltaic mode
2. Photoconductive mode



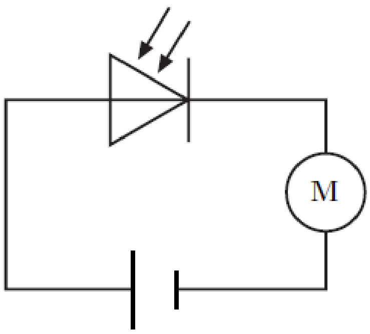
1. Photovoltaic mode:

- In this case the photodiode acts as the power source to the motor. This is how solar cells work.
- When a photon of light falls on the junction its energy is absorbed, producing electron-hole pairs and subsequently a voltage.



2. Photoconductive mode:

- In this case the photodiode acts as a light sensor.
- It is reverse-biased and would not normally conduct (in dark conditions).
- However when intense light falls on the junction it releases electrons and creates electron-hole pairs.
- This decreases the depletion layer and its resistance and therefore allows a current to flow.
- As resistance decreases with light intensity this is called a **Light Dependent Resistor (LDR).**
- The switching action of this reverse-bias mode is extremely fast and can even be used in light gates.



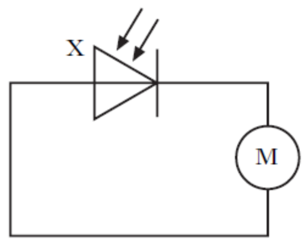
Summary:

p-n junction diode	Forward bias – conducts Reverse bias – does not
LED	Forward bias – conducts and emits light Reverse bias – does not conduct, does not emit light
Photodiode	No bias – photovoltaic mode – acts like a solar cell Reverse bias – photoconductive mode – acts like an LDR

Multiple-choice Examples

Old Higher 2007 Qu: 18:

18. In the following circuit, component X is used to drive a motor.



Which of the following gives the name of component X and its mode of operation?

	Name of component X	*Mode of operation*
A	light-emitting diode	photoconductive
B	light-emitting diode	photovoltaic
C	photodiode	photoconductive
D	photodiode	photovoltaic
E	op-amp	inverting

Revised Higher 2014 Qu: 19:

19. A student makes the following statements about p-n junction devices.

I In solar cells, a potential difference is produced when photons are incident on the junction.

II The photovoltaic effect occurs in solar cells.

III In LEDs, photons are emitted from the junction when a current is passed through it.

Which of these statements is/are correct?

A I only

B III only

C I and II only

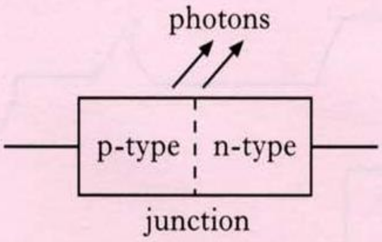
D I and III only

E I, II and III

Paper 2 Examples

Old Higher 2004 Qu: 29(a)-(b):

29. An LED consists of a p-n junction as shown.



(*a*) Copy the diagram and add a battery so that the p-n junction is forward-biased. **1**

(*b*) Using the terms *electrons, holes* and *photons*, explain how light is produced at the p-n junction of the LED. **1**

Semiconductors and p-n junctions homework **Due date:________________**

1.

A crystal of silicon is "doped" with arsenic, that is, 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.

2.

Which of the following statements is/are true?

I In a light emitting diode, positive and negative charge carriers recombine to emit light.

II In a p–n junction diode, the majority carriers in the p-type material are electrons.

III In a photodiode, electron-hole pairs are produced by the action of light.

A I only

B I and II only

C I and III only

D II and III only

E I, II and III

3.

A student reads the following passage in a physics dictionary.

"... a solid state device in which positive and negative charge carriers are produced by the action of light on a p–n junction."

The passage describes a

A light emitting diode

B laser

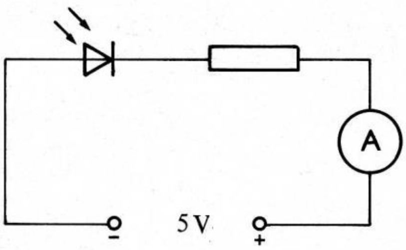
C capacitor

D photodiode

E thermistor.

4.

The circuit below shows a photodiode connected in series with a resistor and an ammeter. The power supply has an output voltage of 5 V and negligible internal resistance.



In a darkened room, there is no current in the circuit.
When light strikes the photodiode, there is a current in the circuit.

(*a*) Describe the effect of light on the material of which the photodiode is made. **1**

(*b*) In which mode is the photodiode operating? **1**

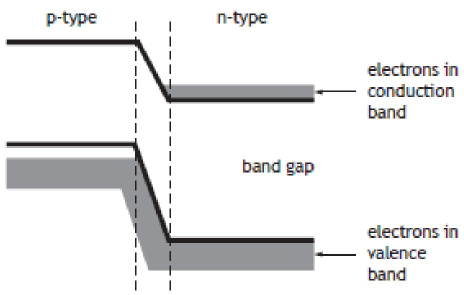
5.

The student connects a red LED and a blue LED, in turn, to the battery.

The LEDs are forward biased when connected.

The student observes that the battery will operate the red LED but not the blue LED.

The diagram represents the band structure of the blue LED.

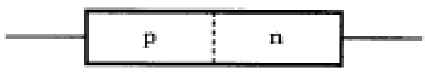


LEDs emit light when electrons fall from the conduction band into the valence band of the p-type semiconductor.

Explain, using band theory, why the blue LED will not operate with this battery.

6.

(*a*) The diagram below represents the p–n junction of a light emitting diode (LED).



(i) Draw a diagram showing the above p–n junction connected to a battery so that the junction is forward biased.

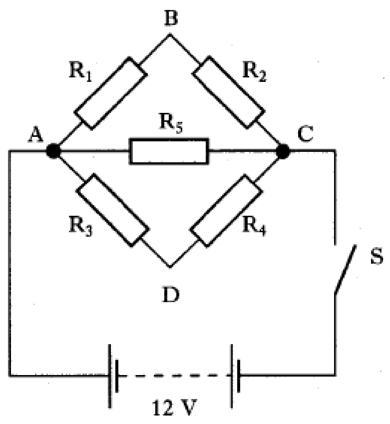
(ii) When the junction is forward biased, there is a current in the diode. Describe the movement of the charge carriers which produces this current.

(iii) Describe how the charge carriers in the light emitting diode enable light to be produced.

Electricity Revision Questions

1. CIRCUITS

Four 10 Ω resistors R_1, R_2, R_3 and R_4 are connected in the form of a square ABCD. A fifth resistor R_5 of the same value is connected between A and C. This arrangement of resistors is connected in a circuit as shown below. The battery in the circuit has negligible internal resistance.



(*a*) Determine the total resistance between A and C.

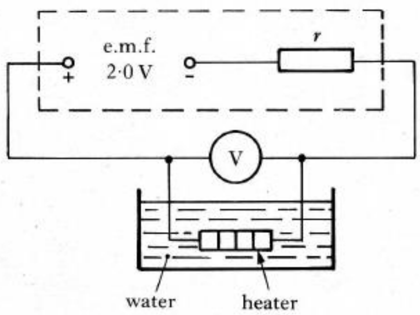
(*b*) The switch S is now closed.

(i) In which of the resistors is the greatest power developed?

(ii) Calculate the value of **this** power.

2. EMF AND INTERNAL RESISTANCE

A heater of resistance 0·32 ohms is connected to a power supply of e.m.f. 2·0 volts and internal resistance *r* as shown below.



(*a*) State what is meant by the term electromotive force (e.m.f.). **1**

(*b*) The power output of the **heater** is 8·0 watts.

Calculate:

(i) the current in the heater;

(ii) the reading on the voltmeter;

(iii) the internal resistance of the power supply. **5**

(*c*) Another identical heater is now placed in the water and connected in parallel with the original heater.

The rest of the circuit is unaltered.

How does this affect the rate at which heat is supplied to the water?

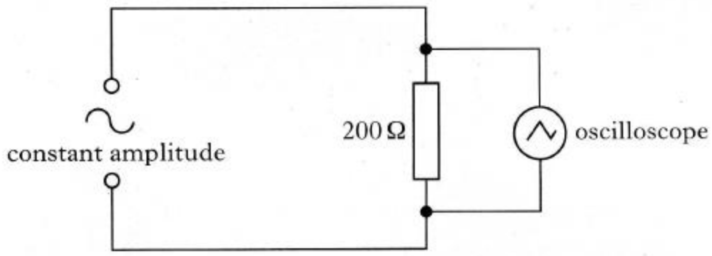
Justify your answer by calculation. **3**

(9)

3. AC & VOLTAGE

Marks

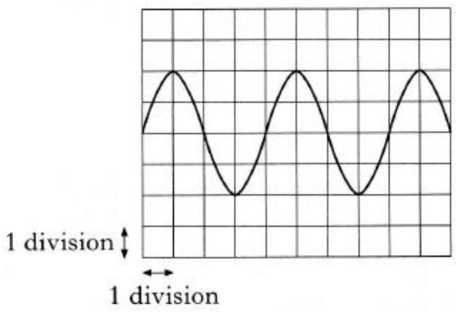
A circuit is set up as shown below. The amplitude of the output voltage of the a.c. supply is kept constant.



The settings of the controls on the oscilloscope are as follows:

y-gain setting = 5 V/division
time-base setting = 2·5 ms/division

The following trace is displayed on the oscilloscope screen.

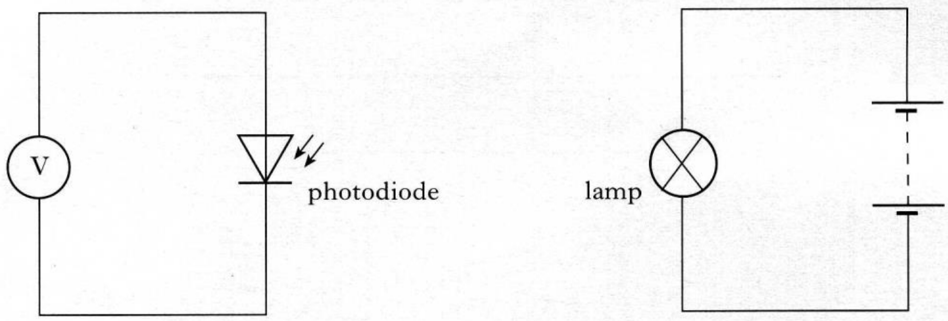


(*a*) (i) Calculate the frequency of the output from the a.c. supply.

(ii) Calculate the **r.m.s. current** in the 200 Ω resistor. **5**

4. P-N JUNCTIONS

The diagram shows a photodiode connected to a voltmeter. A lamp is used to shine light onto the photodiode.



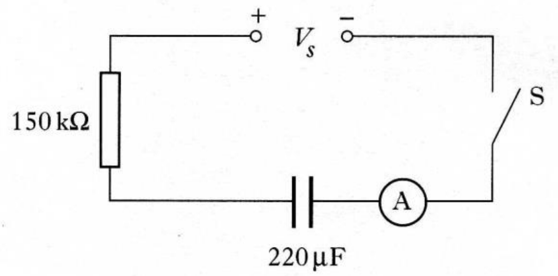
The reading on the voltmeter is 0·5 V.

The lamp is now moved closer to the photodiode.

Using the terms **photons**, **electrons** and **holes**, explain why the voltmeter reading changes.

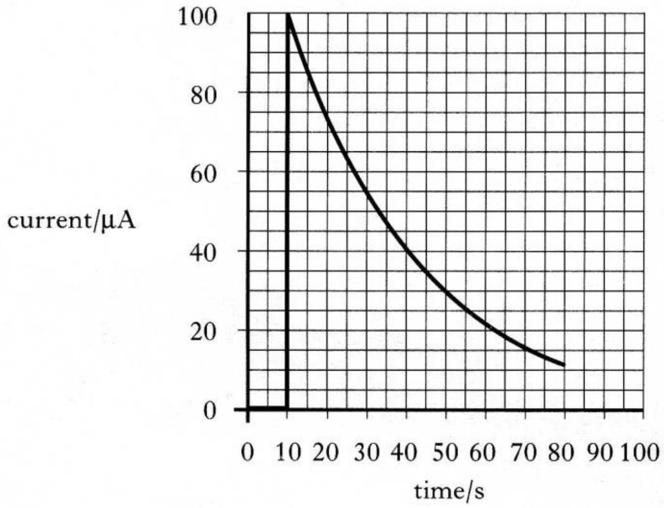
5. Capacitors

(*a*) A capacitor of capacitance 220 μF is connected in series with a 150 kΩ resistor, a switch and an ammeter. A d.c. power supply of negligible internal resistance is connected to the circuit as shown below.



A stopclock is started and after 10 seconds the switch S is closed. Ammeter readings are noted at regular intervals until a time of 80 s is shown on the stopclock.

The graph below shows how the current in the circuit varies with time.



(i) Calculate the voltage V_s of the d.c. power supply.

(ii) At what time on the stopclock does the p.d. across the resistor equal 6 V?

(iii) What is the p.d. across the capacitor when the p.d. across the resistor is 6 V?

(*b*) A magazine article on the resuscitation of a heart attack victim describes the equipment used. This equipment uses a 16 μF capacitor which is charged until the p.d. across it is 6 kV. The capacitor is then fully discharged to give the heart a shock. The discharge time is 2 ms.

(i) When the capacitor is fully charged, calculate:

(A) the charge stored;

(B) the energy stored.

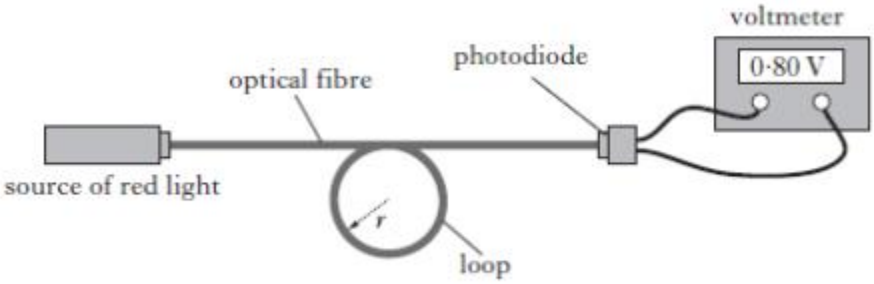
(ii) Calculate the average current during discharge.

6. Open-ended

Marks

A group of students carries out an experiment to investigate the transmission of light through an optical fibre.

Red light is transmitted through a loop of optical fibre and detected by a photodiode connected to a voltmeter as shown.



The photodiode produces a voltage proportional to the irradiance of light incident on it.

The students vary the radius, r, of the loop of optical fibre and measure the voltage produced by the photodiode.

The results are shown in the table.

Radius of loop/mm	*Voltage*/V
5	0·48
10	0·68
15	0·76
20	0·79
30	0·80
40	0·80

(*a*) Using the square ruled paper provided, draw a graph of these results. **2**

(*b*) For use in communication systems, the amount of light transmitted through a loop of optical fibre must be at least 75% of the value for the fibre with no loop.

With no loop in this fibre the reading on the voltmeter is 0·80 V.

Use your graph to estimate the minimum radius of loop when using this fibre in communication systems. **1**

(*c*) Using the same apparatus, the students now wish to determine more precisely the minimum radius of loop when using this fibre in communication systems.

Suggest **two** improvements to the experimental procedure that would achieve this. **2**

(*d*) Describe further experimental work that could be carried out to investigate another factor that may affect the transmission of light through an optical fibre. **2**

(7)

Homework Numerical Answers

AC & Voltage: 1. D; 2. B; 3; B; 4. (a) 7.07 V (b) 625 Hz

Current, potential difference, resistance & power: 1. (a) 5 V (b) 2.5 V 2. B 3. C 4. C
5. C 6. (a)(i) 1800 Ω (ii) – (iii) 5.2 V

Internal resistance: 1. E 2. B 3. D 4. (a) – (b)(i) 5 A (ii) 1.6 V (iii) 0.08 Ω (c) –

Internal resistance & EMF from a graph: 1. (a)(i) – (ii) 1.6 Ω (iii) 1.43 V

2. (b)(i) tpd + lost volts (ii) E=1.4 V; r=0.4Ω (iii) –

Capacitance: 1. B 2. E 3. D 4. E 5. (a) - (b) 4.4×10^{-4} A (c)(i) 0.0405 J (ii) –

6. (a)(i) 1.6×10^{-5} F (ii) 17 +/- 1 µF (iii) –

Semiconductors / p-n: 1. D 2. C 3. D 4. (a) – (b) – 5.

Electricity revision Past Paper questions

Year	Questions Multi-Ch	 Section B
CfE 2018	15,16,17,18,19,20	2(a)(ii),11,12
CfE 2017	16,17,18,19	12,13,14,15
CfE 2016	17,18,19,20	11,12,13
CfE 2015	17,18,19	10,11
CfE Spec	14,16,17,18,19	13, 14
Rev. 2015	17,18,19	30,31
Rev. 2014	15,16,17,18,19	30, 31
Rev. 2013	17,18,19,20	30, 31
Rev. 2012	17,18,19,20	31, 32
Rev. Spec	11,12,13,14	30
2015	8,10,11	25,26,27,28(a)
2014	8,9,10,11,18	25,26,27(a)
2013	10,11,18	25,26,27
2012	8,9,10,11,	25,26
2011	8,11,12,13	24, 25 (a, b)
2010	9,12,16	24,26
2009	9,11,17,19	24,25(a),26
2008	9,10,18	21(c),24,25
2007	8,9,10,18	25,26
2006	8,9,11	25,26(a),27)a)(i)
2005	7,9	21(b)(i),25,26
2004	12,17	24,25,29
2003	8,9,10,11,12,13,14,19	25,
2002	8,10,11,12,18	24
2001	8,9,10	24,25
2000	8	24,25,26