Beatty Secondary School
Secondary 4E Pure Physics
Electromagnetic Induction

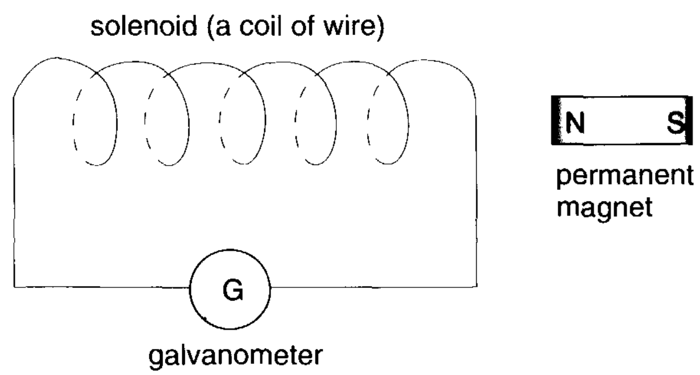
Name: ______________________________ (   )   Class: ___________   Date: _______________

Learning Outcomes

(a) deduce from Faraday's experiments on electromagnetic induction or other appropriate experiments:
  (i) that a changing magnetic field can induce an e.m.f. in a circuit
  (ii) that the direction of the induced e.m.f. opposes the change producing it
  (iii) the factors affecting the magnitude of the induced e.m.f.
(b) describe a simple form of a.c. generator (rotating coil or rotating magnet) and the use of slip rings (where needed)
(c) sketch a graph of voltage output against time for a simple a.c. generator
(d) describe the use of a cathode-ray oscilloscope (c.r.o.) to display waveforms and to measure potential differences and short intervals of time (detailed circuits, structure and operation of the c.r.o. are not required)
(e) interpret c.r.o. displays of waveforms, potential differences and time intervals to solve related problems
(f) describe the structure and principle of operation of a simple iron-cored transformer as used for voltage transformations
(g) recall and apply the equations $V_P / V_S = N_P / N_S$ and $V_P I_P = V_S I_S$ to new situations or to solve related problems (for an ideal transformer)
(h) describe the energy loss in cables and deduce the advantages of high voltage transmission

A) Faraday's experiment

Experiment to show that a changing magnetic field can induce an e.m.f. in a circuit



1. Set up the apparatus as shown in the diagram.
2. A permanent magnet is inserted into a solenoid connected to a sensitive galvanometer.
3. The galvanometer needle deflects as the permanent magnet move within the solenoid.
4. This shows that **e.m.f.** can be induced when there is a changing magnetic field.
5. This process is called **electromagnetic induction**.

Note:
Both e.m.f. and current are induced in a conducting wire when it is put in a changing magnetic field. So when e.m.f. is said to be induced in a coil, it should be understood that current is also induced at the same time.

Definitions

1. Electromagnetic induction is the **process through which an induced e.m.f is produced in a conductor due to a changing magnetic field**.
2. Induced current is **a current produced in a conducting wire due to changing magnetic field**.

Factors affecting the magnitude and direction of the induced e.m.f.

Procedure	Galvanometer response
Insert North pole of 1 bar magnet into solenoid	
Insert North pole of 1 bar magnet into solenoid at twice the speed	
Insert North pole of 2 bar magnets into the solenoid	
Insert North pole of 1 bar magnet into a solenoid with twice the number of turns	

From the above process, we deduce that the strength or magnitude of the induced e.m.f. are affected by:

1. The **speed** with which the magnet is inserted into or withdrawn from the solenoid.

2. The **magnetic field strength** of the magnet.

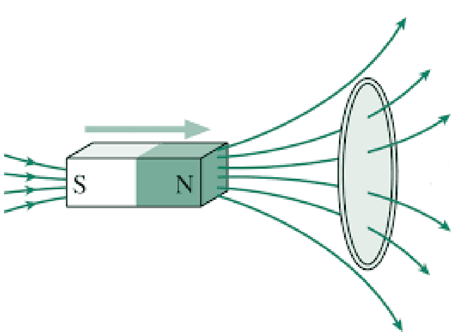
3. The **number of turns** in the solenoid.

Determine the direction of induced current during electromagnetic induction

Procedure	Galvanometer response
Insert North pole of 1 bar magnet into solenoid	
Withdraw the same bar magnet out of solenoid	
Insert South pole of 1 bar magnet into solenoid	
Withdraw the same bar magnet out of solenoid	
Solenoid move towards North pole of magnet	
Solenoid withdraw from the same magnet	

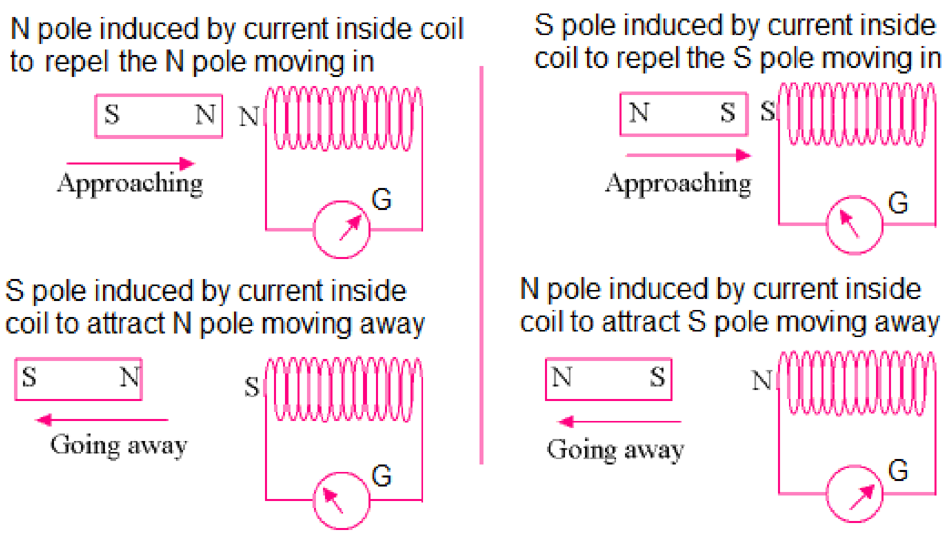
Laws of electromagnetic induction

1. Faraday's Law of electromagnetic induction **states that the magnitude of the induced e.m.f in a circuit is directly proportional to the rate of change of magnetic flux in the circuit.**



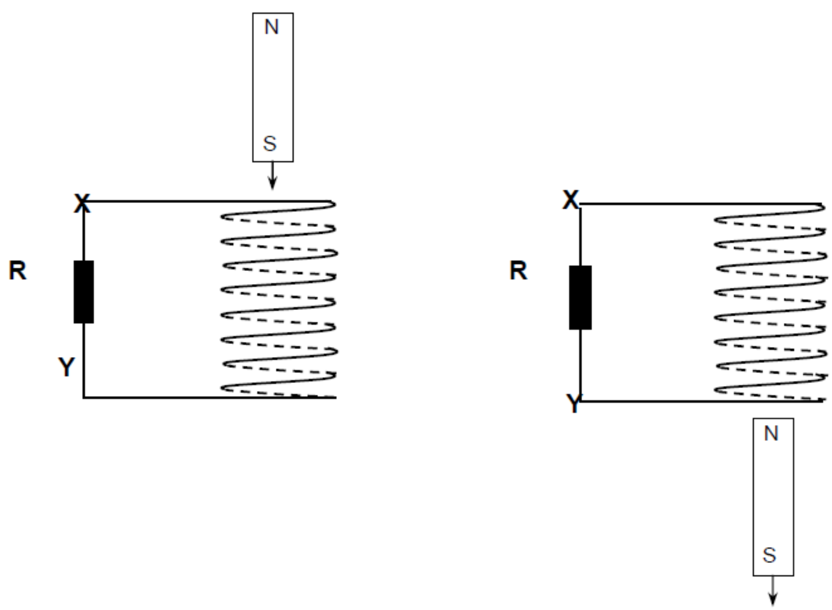
More magnetic field lines pass through the loop per second when the magnet moves right

2. Lenz's Law states that **the direction of the induced e.m.f and hence the direction of induced current in a closed circuit, is always such that its magnetic effect opposes the motion or change producing it.**



Practice

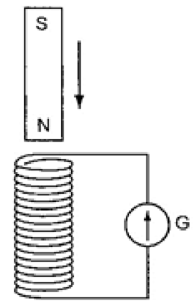
1. The diagrams below show the set-up for which a short bar magnet is dropped through a coil of wire.



Which row correctly indicates the direction of the induced current via the load **R** in the circuit?

	Magnet entering the coil	Magnet leaving the coil
A	**X** to **Y**	**X** to **Y**
B	**X** to **Y**	**Y** to **X**
C	**Y** to **X**	**X** to **Y**
D	**Y** to **X**	**Y** to **X**

2. A small coil is connected to a galvanometer as shown. When the magnet is allowed to fall towards the coil, the galvanometer pointer gives a momentary deflection to the right of the zero position.



The magnet moves through the coil and, as it falls away from the coil, the galvanometer pointer ………… .

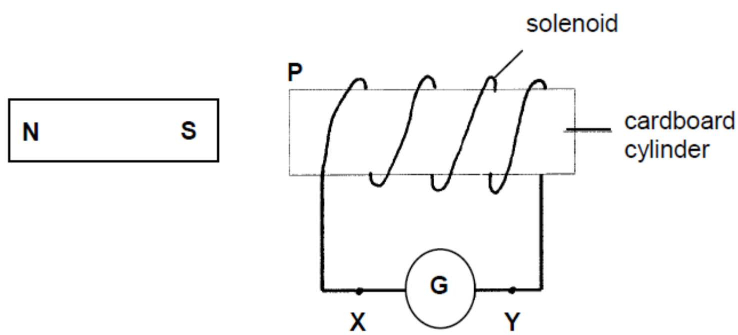
A gives a continuous reading to the left.

B gives a continuous reading to the right.

C gives a momentary deflection to the left.

D gives a momentary deflection to the right.

3. The **S** pole of a bar magnet is pushed into a solenoid, as shown in the diagram. An electromotive force is induced which causes the induced current to flow from **X** to **Y** through the galvanometer.



Which action, using the **same end P** of the solenoid, would produce an induced current flowing in the same direction?

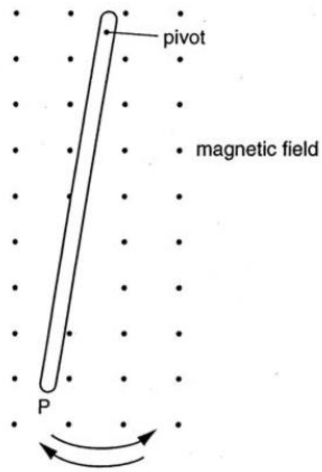
A Pulling a **S** pole out of the solenoid

B Pushing a **N** pole into the solenoid

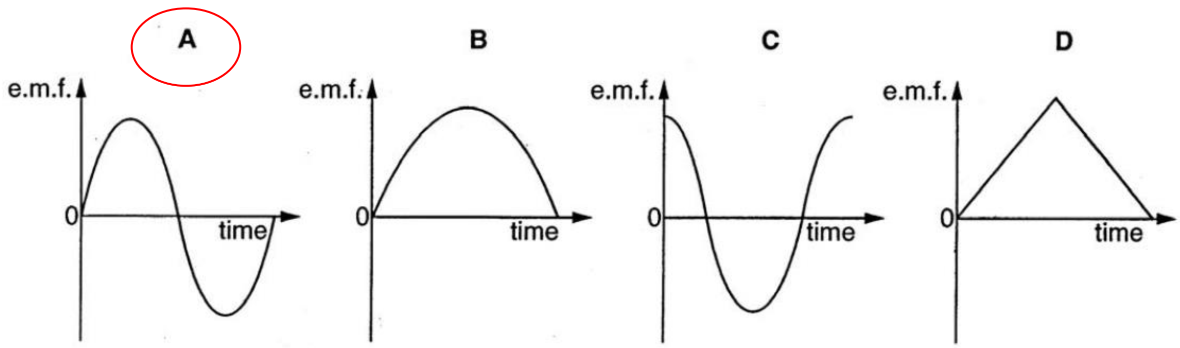
C Pulling the solenoid away from a **N** pole

D Pulling the solenoid away from a **S** pole

4. The diagram shows a metal bar swinging like a pendulum across a uniform magnetic field. The motion induces an e.m.f between the ends of the bar.

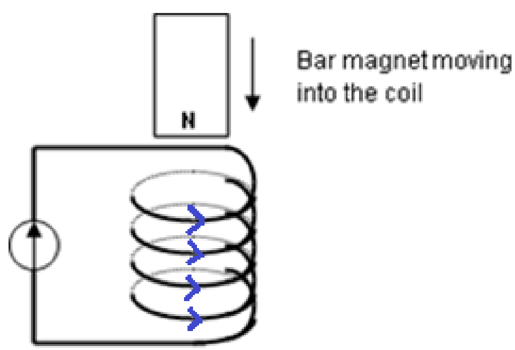


Which graph represents this e.m.f during one complete oscillation of the bar, starting and finishing at P?



5. The figure below shows a solenoid and a permanent magnet.

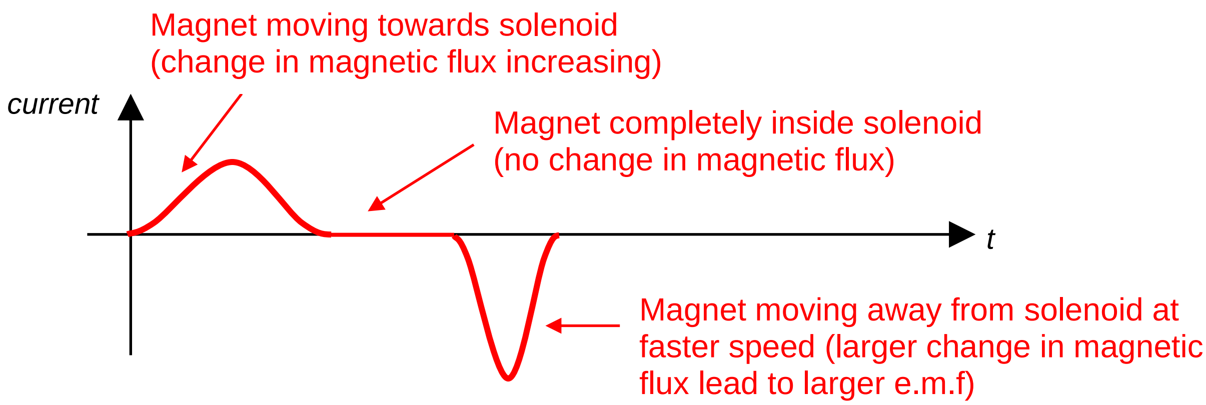
a) On the figure, draw the induced current flowing in the solenoid owing to the presence of the induced e.m.f when the magnet dropped into the solenoid.



b) Explain why there is an induced e.m.f in the coil.

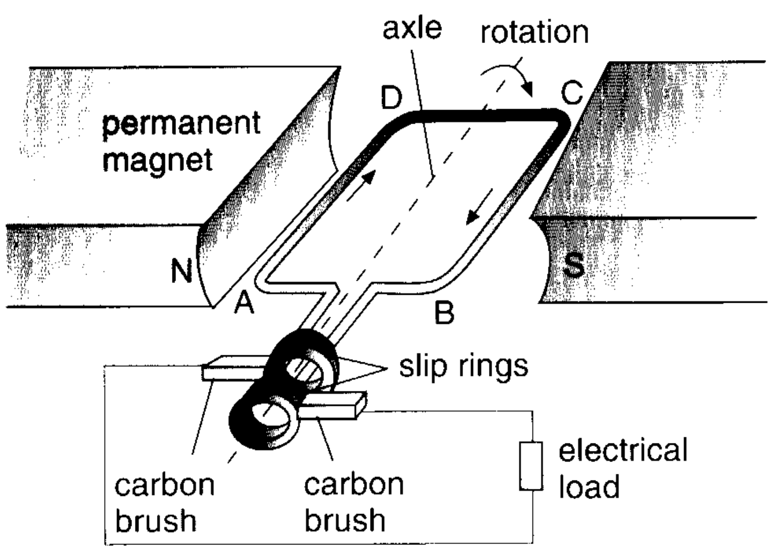
There is an induced e.m.f because there is a change in the magnetic flux inside the coil as the magnet enters and exits the coil.

c) The magnet is dropped through a solenoid. Sketch a graph of the current reading against time on the axes below.



B) Alternating Current Generator

A generator is an electromagnetic device which transforms **mechanical energy** into **electrical energy.** **(Output: Alternating Current)**.



How it works?

1. By turning the axle, the coil is made to rotate between the poles of a permanent magnet.
2. As the coil rotates, the magnetic field through the coil changes.
3. E.m.f or current is induced between the ends of the coil.
4. The induced current does not flow until the ends of the coil are connected to an external circuit with an electrical load (resistor).

What is the use of the slip ring?

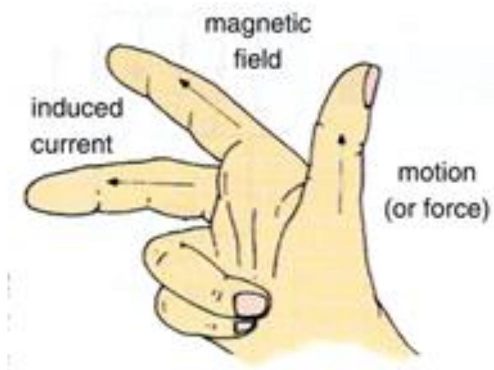
The slip rings ensure that the direction of the induced current flowing in the external circuit changes every half-revolution. The output current becomes alternating (AC).

What is the use of carbon brushes?

They provide electrical contacts between the rotating slip rings and the external circuit.

Fleming’s Right-hand rule

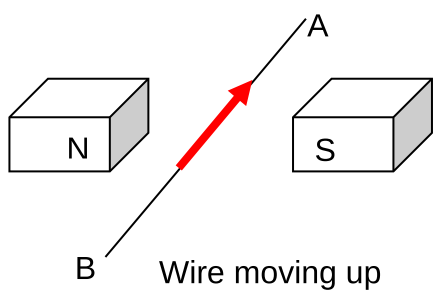
Given the direction of the magnetic field and force, the direction of the induced current can be found using Fleming’s right-hand rule.



Practice

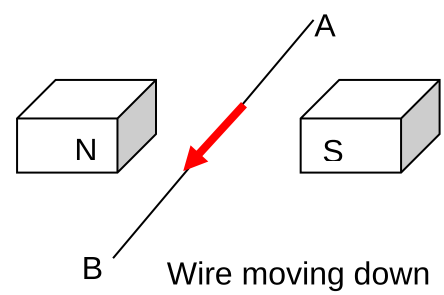
Use Fleming’s right- hand rule to determine and indicate the direction of the induced current on the diagrams below.

a)



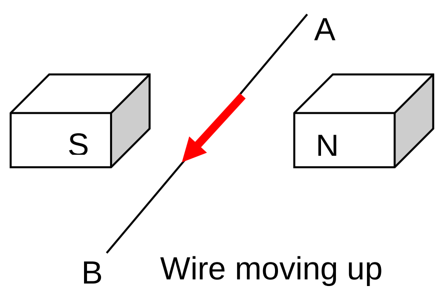
Wire moving up

b)



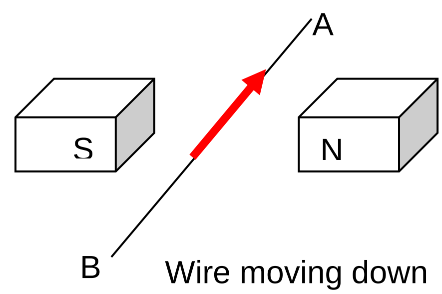
Wire moving down

c)



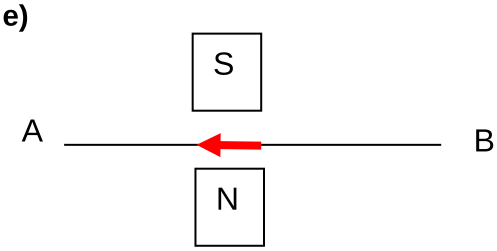
Wire moving up

d)



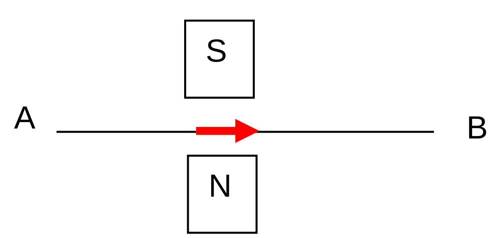
Wire moving down

e)



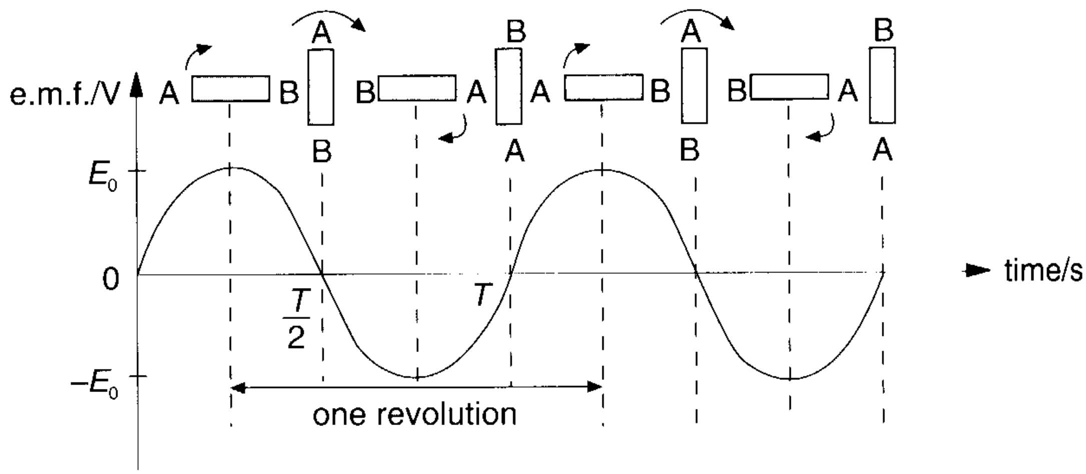
Wire moving *out* of the paper

f)



Wire *into* of the paper

C) **Output graph of an AC Generator (Induced e.m.f. versus time)**



Interpretation of the output graph

1. Maximum output (E_0 and $-E_0$) always correspond to the time when the coil is **parallel** to the magnetic field.

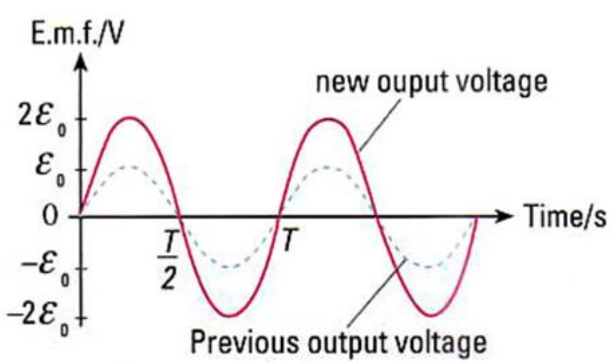
   *This is because the sides of the coil are **cutting through the magnetic field lines** (i.e change in magnetic flux linkage) at the **greatest rate**.*

2. Minimum output (when E = 0) always correspond to the time when the coil is **perpendicular** to the magnetic field.

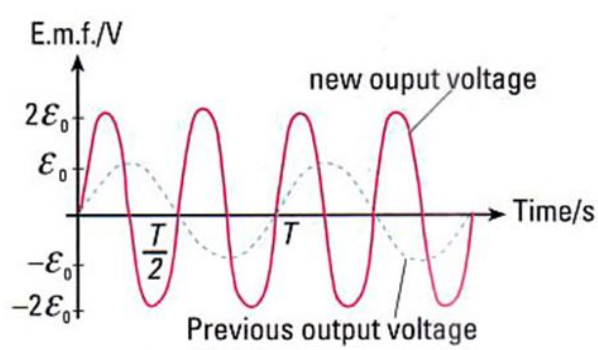
   *This is because in this position, the sides of the coil are **not cutting through any magnetic field lines**. Therefore its output is zero.*

Ways to increase the induced e.m.f for an AC Generator

1. increase the **number of turns** in the rotating coil
2. increase the **magnetic field strength** of the permanent magnets
3. increase the **speed** of rotation (increase in mechanical energy)
4. insert a **soft-iron core** between the magnets and the coil to help concentrate the magnetic field lines around the rotating coil



Doubling the number of turns of the coil will double the maximum output voltage.

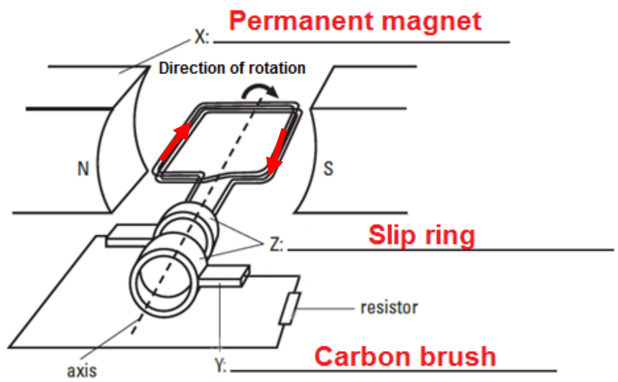


Doubling the frequency f doubles the maximum output voltage.

Practice

1 The figure shows an AC generator.

a) Write down the missing labels X, Y and Z on the diagram.

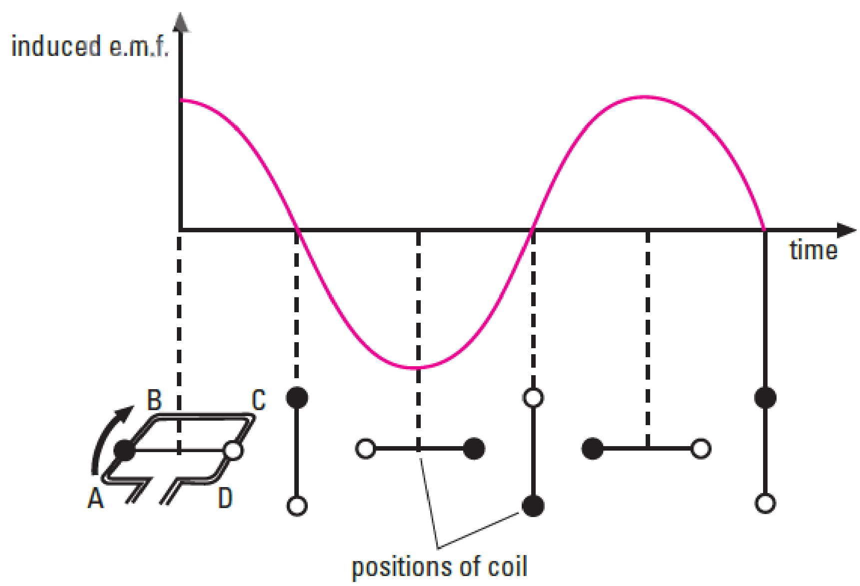


b) Explain the purpose of part Y and Z.

Part Z (slip ring) maintains constant electrical contact between coil and carbon brush, and at the same time maintains freedom of rotation, hence allowing the direction of current inside the external circuit to reverse direction every half revolution.
Part Y (carbon brush) allows slip rings to be in constant contact with the external circuit.

c) The coil is rotated in the clockwise direction as shown. On the figure, indicate the direction of the induced current in the coil in the instance shown.

d) Sketch the graph which shows the variation of the induced e.m.f. when the coil is rotated.



D) Transformers (Step-up and step-down)

- A transformer is a device that can change a high alternating voltage (at low current) to a low alternating voltage (at high current), or vice versa.
- A step-down transformer is a device that changes a **high** alternating voltage to a **low** alternating voltage.
- A step-up transformer is a device that changes a **low** alternating voltage to a **high** alternating voltage.

	Step-up		**Step-down**	
	Primary coil	**Secondary coil**	**Primary coil**	**Secondary coil**
Number of turns	Fewer turns	More turns	More turns	Fewer turns
Voltage	Low	High	High	Low
Current	High	Low	Low	High

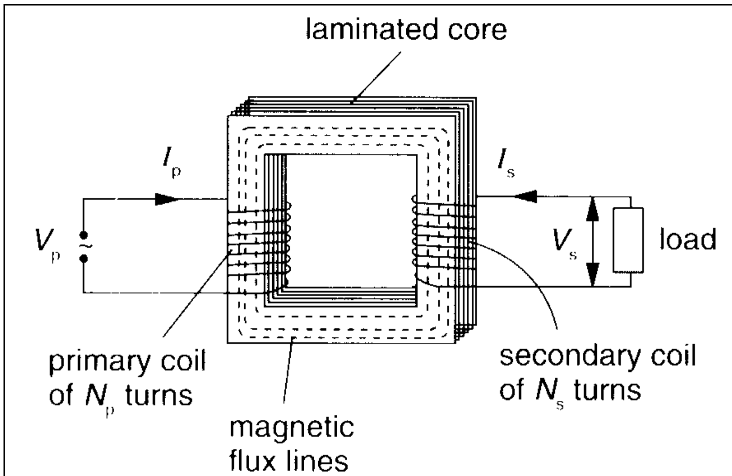
Parts of a transformer

1. A primary and a secondary coil.

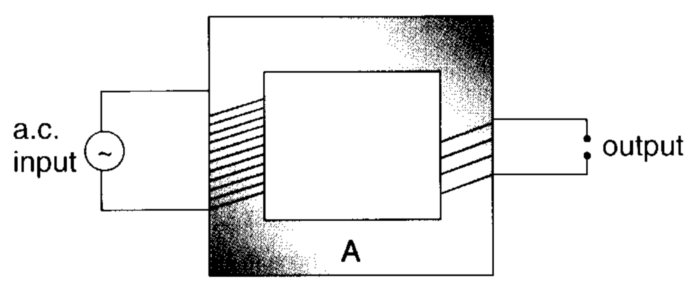
   The primary and the secondary coil never have the same number of turns.
   Primary coil has more turns than secondary coil means it is a **step-down** transformer.
   Primary coil has lesser turns than secondary coil means it is a **step-up** transformer.

2. Laminated soft-iron core concentrates the magnetic field lines around the two coils.

3. The coil attached to an electrical load or output is always the secondary coil.



Example of a step-down transformer



How it works?

1. It transfers electrical energy from primary coil to secondary coil.
2. At the primary coil, an alternating current sets up a **changing magnetic field**.
3. This changing magnetic field induces an e.m.f. in the secondary coil.

Will direct current (DC) power supply work in a transformer?

No. An alternating current is needed to set up a **changing magnetic field** around the primary coil. A DC power supply will only set up a constant magnetic field which does not change.

Formula

$$\frac{N_s}{N_p} = \frac{V_s}{V_p}$$

Note: $\frac{N_s}{N_p}$ is also known as the **turn ratio**.

V_p = input voltage (E.M.F.) in the primary coil N_p = number of turns in the primary coil I_p = current in the primary coil	V_s = induced output voltage (e.m.f.) in the secondary coil N_s = number of turns in the secondary coil I_s = induced current in the secondary coil

E) Power Transmission in Transformer

Ideal transformer assumes that that the power supplied by the primary coil is fully transferred to the secondary coil. Using principles of conservation of energy,

$$I_p V_p = I_s V_s$$

Putting the two formulas together we have

$$\frac{N_s}{N_p} = \frac{V_s}{V_p} = \frac{I_p}{I_s}$$

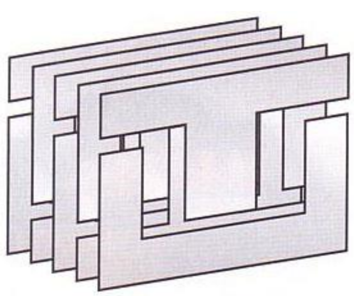
In reality, transformers are not ideal. The efficiency can be calculated using the formula.

$$\text{Efficiency} = \frac{\text{Total useful output power}}{\text{Total input power}} \times 100\%$$

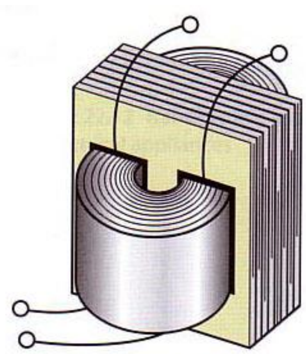
Efficiency is the **ratio of the total useful output power to the total input power expressed as a percentage**.

How is energy loss reduced in a transformer?

1. Effective **soft magnetic material** for the core to allow magnetic fields to change easily.
2. A **laminated** core design to reduce the flow of eddy currents (current induced within the iron core itself).
3. Special core design (e.g. using thin sheets of iron for the core) to ensure magnetic field produced by primary coil is linked completely to the secondary coil.
4. **Low resistance copper wires** should be used to reduce energy lost in the form of heat.

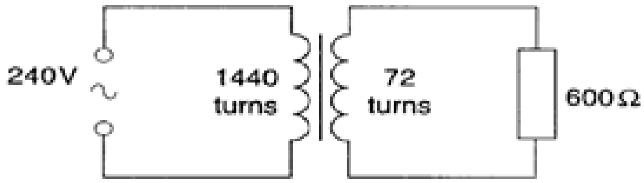


laminated iron core



Practice

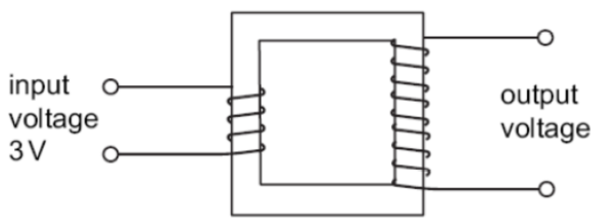
1 Figure below shows an ideal transformer. There are 1440 turns on the primary coil and 72 turns on the secondary coil. The primary coil is connected to a 240 V mains supply. A resistor of resistance 600 Ω is connected across the secondary coil.



Assume that the transformer has an efficiency of 100 %, what are the turns ratio, the voltage across the 600 Ω resistor, the current in the primary coil?

	Turns ratio	**Voltage across 600 Ω resistor**	**Current in the primary coil**
A	0.05	240 V	0.02 A
B	0.05	12 V	0.001 A
C	20	12 V	0.02 A
D	20	12 V	0.4 A

2 A step-up transformer with 100 % efficiency has an input voltage of 3 V and an input current of 2 A.



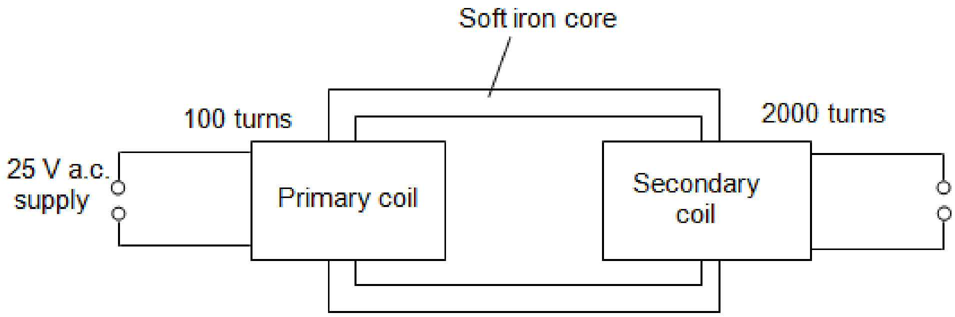
Under these conditions, what output voltage and output current could be obtained?

	Output voltage / V	**Output current / A**
A	1	6
B	2	3
C	4	1
D	6	1

3 A transformer has 100 turns on its primary coil. The current through the primary coil is 75 A. The current through the secondary coil is 15 A. Assuming an ideal transformer with no energy loss to the surroundings, calculate the number of turns in the secondary coil.

A 20 **B** 60 **C** 300 **D** 500

4 In the transformer below, the number of turns in the primary coil is 100 turns, and the number of turns in the secondary coil is 2000 turns. A 25 V a.c. supply is connected to the primary coil.



(a) State the purpose of the core.

The soft iron core strengthens the magnetic field lines linking the primary to the secondary coil.

(b) State and explain if the transformer above is a step-up or a step-down transformer.

Step-up transformer. The number of turns in the secondary coil is more than the number of turns in the primary coil.

(c) Calculate the output voltage in the secondary coil, assuming that the transformer is ideal.

Np / Ns = Vp / Vs
Vs = Vp / (Np / Ns) = 25 / (100 / 2000) = 500 V

(d) In reality, the efficiency of the transformer is only 75%.

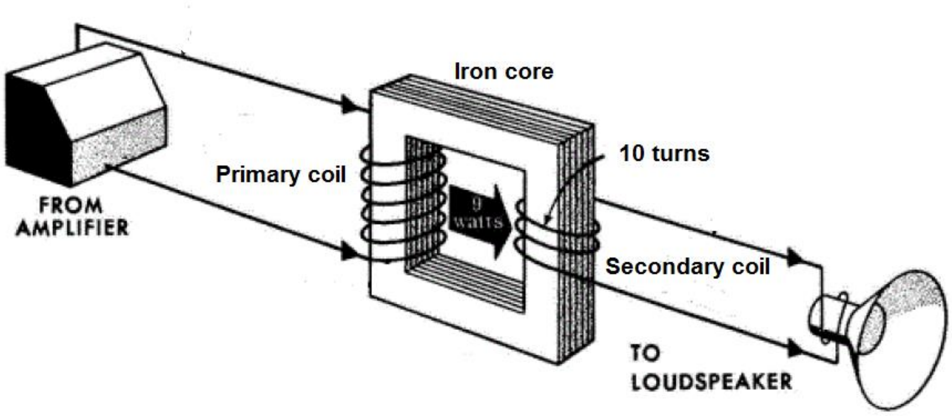
(i) If the current flowing in the primary coil is 2 A, calculate the current flowing in the secondary coil.

P = IV = (2)(25) = 50 W
I = P / V = (50 x 0.75) / 500 = 0.075 A

(ii) State one cause for the power loss in the non-ideal transformer.

Heat loss due to eddy currents induced in the soft iron core
Heat loss due to resistance of the coils
Leakage of magnetic field lines between the primary and secondary coils

5 The figure below shows a transformer with a turns ratio of 1:20 that is used to change the voltage supplied to a loudspeaker.



a) Explain how an e.m.f can be induced across the loudspeaker even though it is not connected to a voltage source.

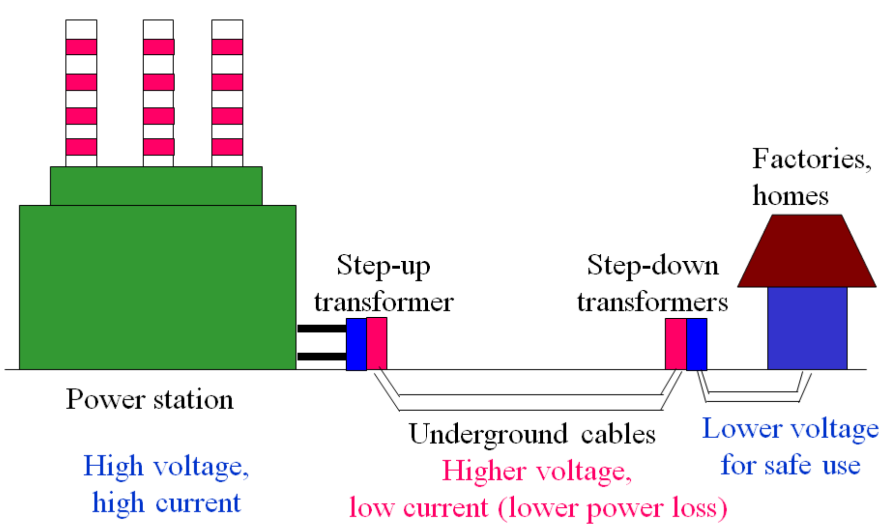
The alternating current flowing in the primary coil causes a constantly changing magnetic field linked to the secondary coil / changing magnetic flux linkage via the soft iron core. According to Faraday's Law, an e.m.f will be induced at the secondary coil across the loudspeaker.

b) The primary voltage from the amplifier is 240 V. It is meant to supply 9.0 W to the loudspeaker. Calculate the current flowing from the amplifier and the current flowing in the loudspeaker. You may assume the transformer is working at 100% efficiency.

Ip = P / Vp = 9 / 240 = 0.0375 A
Np / Ns = Vp / Vs
Vs = Vp / (Np / Ns) = 240 / 20 = 12 V
Is = P / Vs = 9 / 12 = 0.75 A

F) Transmission of electricity

Electricity generated at power station is transmitted to the mains through the use of cables. Generator produces a very high voltage (10 MW or 10 x 10^6 W) of electrical power at around 10 kV.

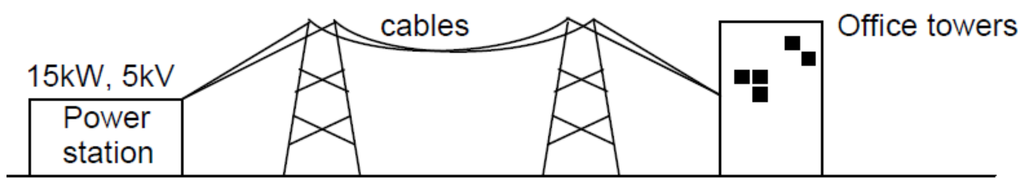


Power loss in transmission (calculated using $P_{loss} = I^2R$) can be reduced by:

1. Using **thicker cables** to reduce resistance to reduce voltage drop across the wires. However, this leads to increased cable cost.
2. Since P = VI, given a **high** voltage across the wires, the current flowing in the cable is **low**. Hence **$P_{loss} = I^2R$** is low. Power loss is minimised and thinner cables can be used.

Practice

1 The figure below shows high voltage cables transmitting electrical energy from the power station to office towers.



The power station generates 15kW of electricity that is transmitted at a voltage of 5kV across the cables. The net resistance of the cables is 200Ω. Calculate the power loss in the cables.

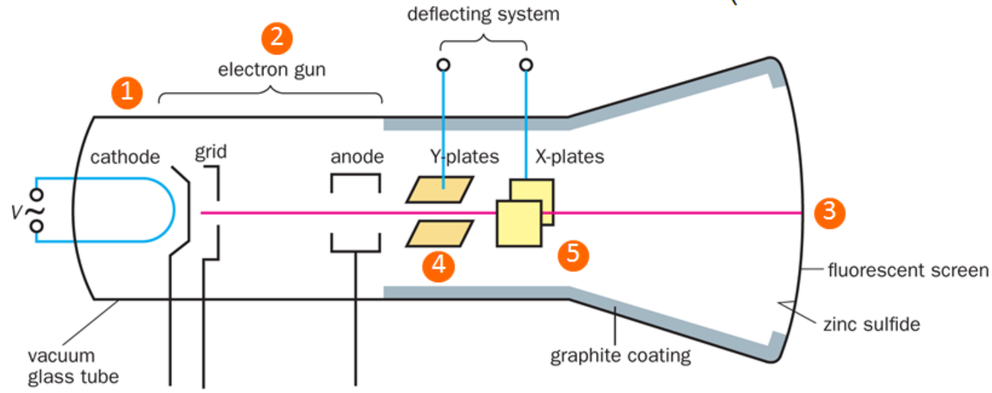
P = VI
I = P / V = 15000 / 5000 = 3 A
$P_{loss} = I^2R = (3)^2(200) = 1800$ W

G) Cathode ray oscilloscope

The cathode ray oscilloscope (c.r.o.) is a device that shows how a voltage varies with time.

2 The electron gun emits a beam of electrons, which are produced by the cathode.

3 A bright spot is created when the electron beam strikes the fluorescent screen (coated with zinc sulfide).



1 The cathode-ray tube consists of a vacuum tube that holds an electron gun, a deflecting system and a fluorescent screen.

4 Varying the voltage across the Y-plates changes the vertical deflection of the electron beam.

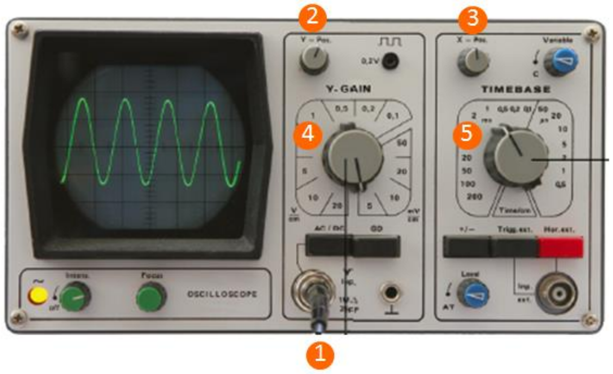
5 Varying the voltage across the X-plates changes the speed at which the electron beam sweeps horizontally across the fluorescent screen.

Using the C.R.O

1 Input voltage

2 Y-shift or Y-offset – shifts entire trace **vertically** up or down

3 X-shift – shifts entire trace **horizontally** left or right



4 Y-gain control – amplifies height of electron beam

5 Time base control – controls speed at which electron beam sweeps across the screen

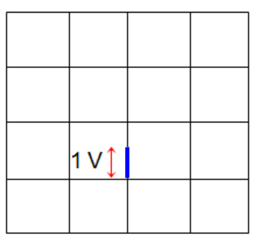
Y Gain: Amplifies the vertical (Y) deflection of the electron beam by varying the voltage applied across the Y-plates of the cathode-ray tube.

Time base: Adjusts how quickly the electron beam sweeps horizontally across the screen. This is done by varying the voltage applied across the X-plates of the cathode-ray tube.

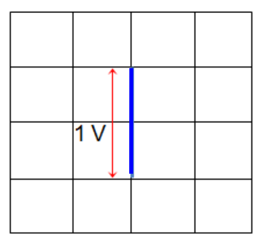
Common uses of the c.r.o

1) Measuring voltage

- The time base is not switched on.
- Connect the voltage to be measured to the input terminal.
- A vertical trace is seen.
- By adjusting the Y-gain, the height of the trace can be magnified so that its magnitude can be read off the screen easily.



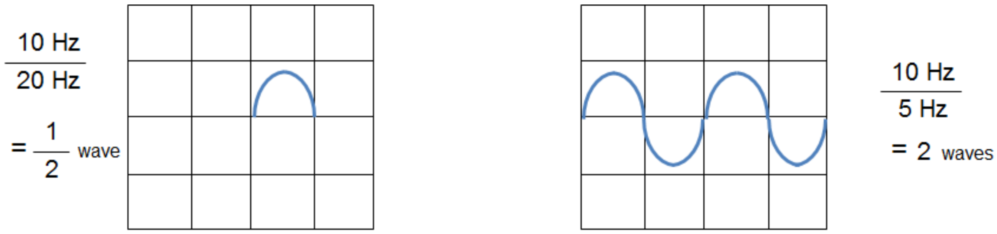
Input voltage = 1 V
Y-gain = 2 V/div



Input voltage = 1 V
Y-gain = 0.5 V/div

2) Displaying voltage waveforms

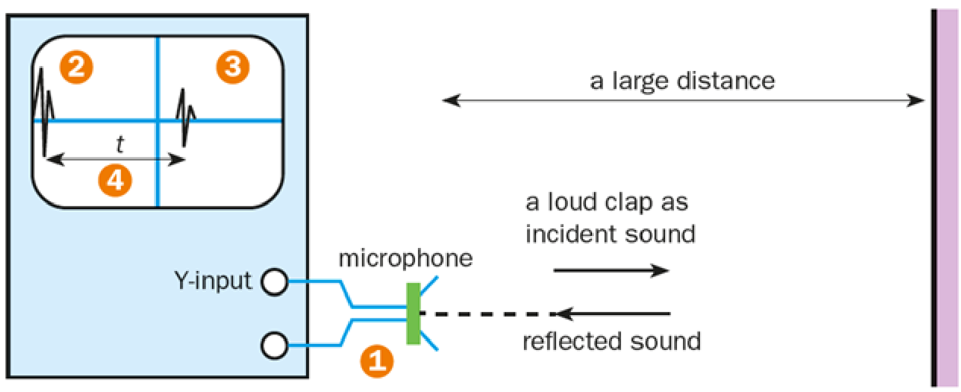
- The time base is switched on.
- Connect the voltage to be measured to the input terminal.
- By adjusting the time base, the width of each wave and number of complete waves displayed can be varied.



Frequency of input voltage = 10 Hz
Time base = 20 Hz

Frequency of input voltage = 10 Hz
Time base = 5 Hz

3) Measuring short time intervals (e.g. time taken for sound to travel)



1 Connect a microphone to the Y-input.

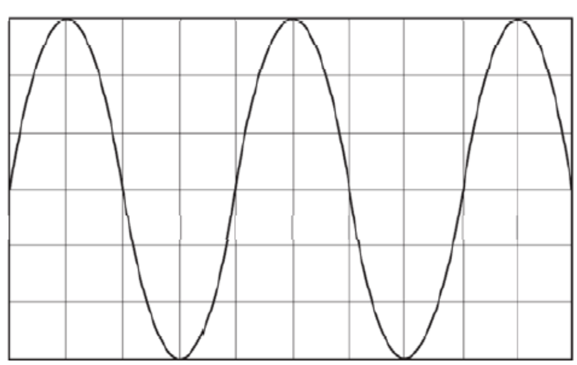
2 Clap once near the microphone. A pulse is received and displayed on the C.R.O.

3 The sound pulse is reflected by the wall. The microphone then receives the echo and it is displayed as shown.

4 Count the number of divisions between the two pulses and calculate the time taken *t*, using the time base setting.

Practice

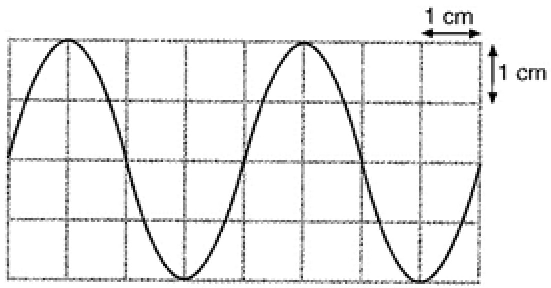
1 The cathode-ray oscilloscope (c.r.o.) display shows the waveform produced by an electronic circuit. The c.r.o. time-base is set at 10 ms per division.



What is the period of the signal shown?

A 20 ms | **B** 30 ms | **C** 40 ms | **D** 60 ms

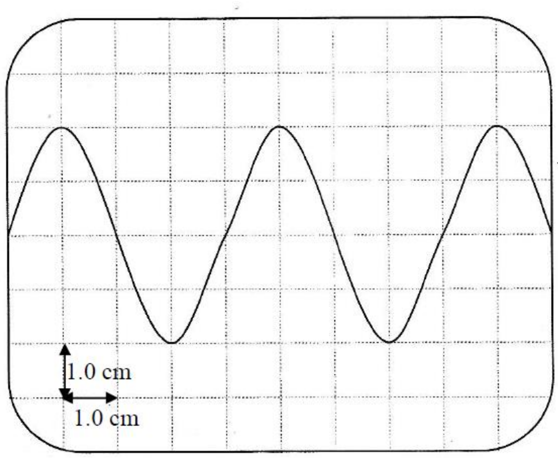
2 The diagram shows a trace on an oscilloscope set at 1.0 V per cm on the vertical axis and 1.0 millisecond per cm on the horizontal axis.



What is the peak voltage and frequency of the alternating voltage applied across Y-plate?

	Peak voltage / V	Frequency / Hz
A	1.5	500
B	1.5	250
C	2.0	125
D	2.0	250

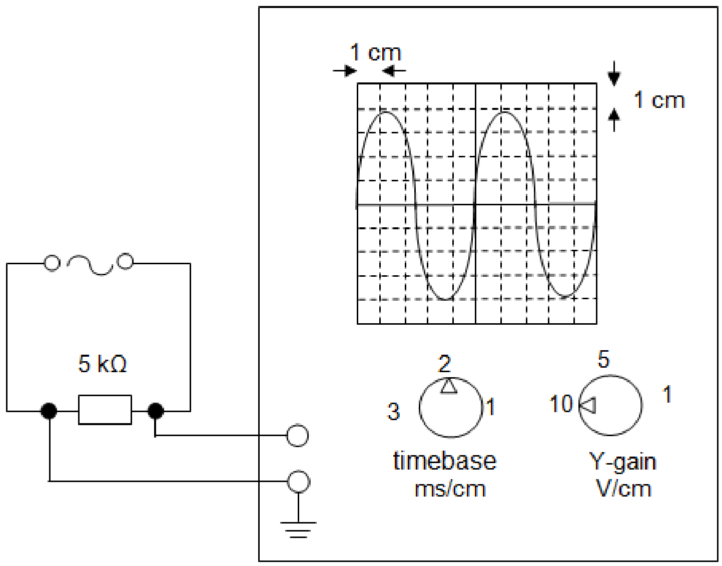
3 The figure shows the reading on a cathode ray oscilloscope. The time-base of the oscilloscope is set to 5.0 ms cm^{-1} and the Y-gain to 1.0 V cm^{-1}.



Which row is correct for the signal shown?

	Frequency / Hz	Peak Voltage / V
A	0.020	4.0
B	0.020	2.0
C	50	2.0
D	50	4.0

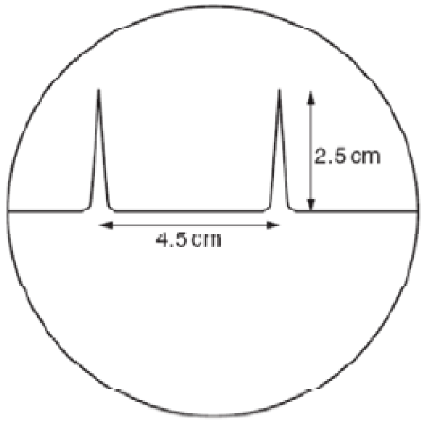
4 The figure below shows a wave display on a cathode ray oscilloscope with the X-gain and Y-gain setting of a circuit connected to it.



What is the peak current and the frequency of the wave?

	peak current	frequency
A	4 mA	5 Hz
B	8 mA	100 Hz
C	8 mA	5 Hz
D	8 A	100 Hz

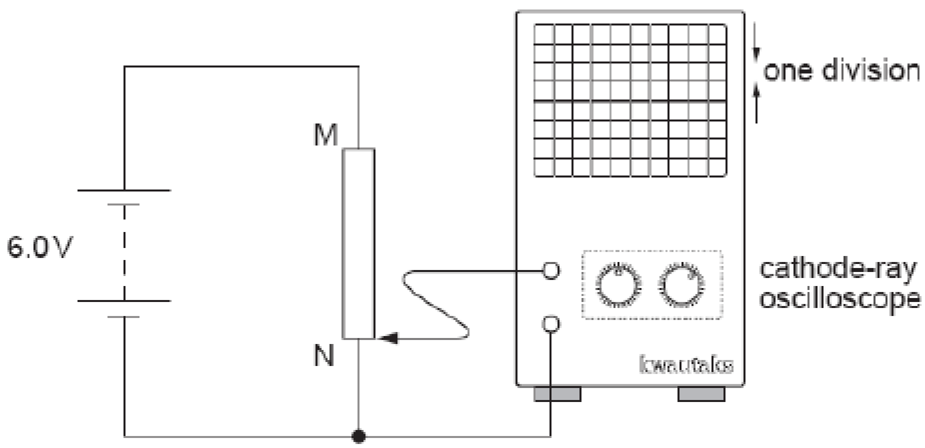
5 A trace consisting of two pulses is recorded as shown in the diagram. The time-base on a cathode-ray oscilloscope is set at 6 ms / cm.



What is the time interval between the two pulses?

A 0.42 ms **B** 0.75 ms **C** 1.33 ms **D** 27 ms

6 The figure below shows two terminals M and N of a potential divider (potentiometer) connected to a 6.0 V battery. The circuit is also connected to a cathode-ray oscilloscope (CRO).



The sliding contact is at N and the trace on the oscilloscope is a horizontal line passing through the centre of the screen. The timebase setting is 1.0 ms/div. The Y-gain setting is 2.0 V / div.

(a) Explain why the trace is a horizontal line through the centre.

When contact is at N, the potential difference is at 0 V.

(b) The sliding contact is moved at a slow uniform rate from N to M. Describe in detail what happens to the trace on the screen.

The trace will be slowly rise vertically to a maximum of 6 V and a horizontal line at 6 V is seen.

(c) Sketch the **final** trace in the grid below.