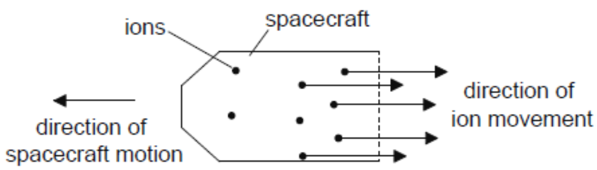
R2019_511P2 *[208 marks]*

Ion-thrust engines can power spacecraft. In this type of engine, ions are created in a chamber and expelled from the spacecraft. The spacecraft is in outer space when the propulsion system is turned on. The spacecraft starts from rest.



The mass of ions ejected each second is 6.6×10^{-6} kg and the speed of each ion is 5.2×10^{4} m s^{-1}. The initial total mass of the spacecraft and its fuel is 740 kg. Assume that the ions travel away from the spacecraft parallel to its direction of motion.

1a. Determine the initial acceleration of the spacecraft. *[2 marks]*

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An initial mass of 60 kg of fuel is in the spacecraft for a journey to a planet. Half of the fuel will be required to slow down the spacecraft before arrival at the destination planet.

1b. Estimate the maximum speed of the spacecraft. *[2 marks]*

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1c. Outline why scientists sometimes use estimates in making calculations. *[1 mark]*

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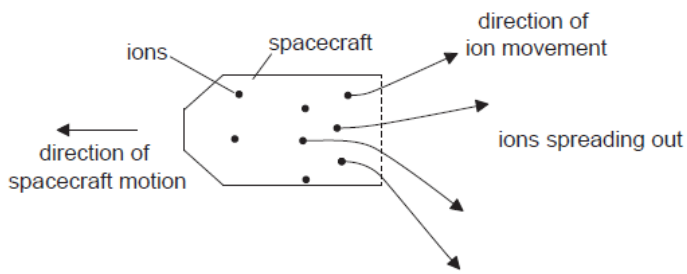
In practice, the ions leave the spacecraft at a range of angles as shown.



1d. Outline why the ions are likely to spread out. *[2 marks]*

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1e. Explain what effect, if any, this spreading of the ions has on the acceleration of the spacecraft. *[2 marks]*

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On arrival at the planet, the spacecraft goes into orbit as it comes into the gravitational field of the planet.

1f. Outline what is meant by the gravitational field strength at a point. *[2 marks]*

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1g. Newton’s law of gravitation applies to point masses. Suggest why the law can be applied to a satellite orbiting a spherical planet of uniform density. *[1 mark]*

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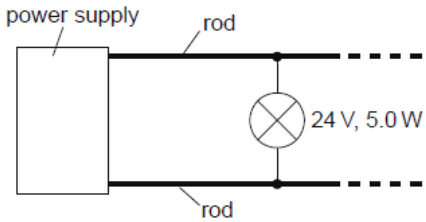
A lighting system consists of two long metal rods with a potential difference maintained between them. Identical lamps can be connected between the rods as required.



The following data are available for the lamps when at their working temperature.

Lamp specifications 24 V, 5.0 W

Power supply emf 24 V

Power supply maximum current 8.0 A

Length of each rod 12.5 m

Resistivity of rod metal $7.2 \times 10^{-7}\,\Omega\,m$

2a. Each rod is to have a resistance no greater than $0.10\,\Omega$. Calculate, in m, the minimum radius of each rod. Give your answer to an appropriate number of significant figures. *[3 marks]*

2b. Calculate the maximum number of lamps that can be connected between the rods. Neglect the resistance of the rods. *[2 marks]*

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2c. One advantage of this system is that if one lamp fails then the other lamps in the circuit remain lit. Outline **one** other electrical advantage of this system compared to one in which the lamps are connected in series. *[1 mark]*

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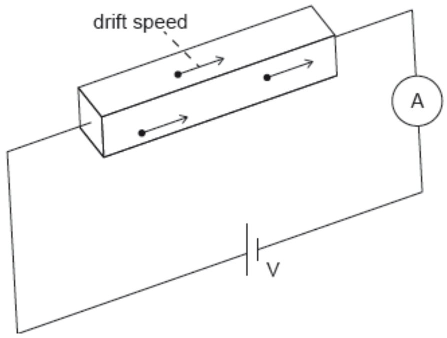
An ohmic conductor is connected to an ideal ammeter and to a power supply of output voltage V.



The following data are available for the conductor:

density of free electrons = 8.5×10^{22} cm^{-3}

resistivity $\rho = 1.7 \times 10^{-8}$ Ωm

dimensions w × h × l = 0.020 cm × 0.020 cm × 10 cm.

The ammeter reading is 2.0 A.

3a. Calculate the resistance of the conductor. *[2 marks]*

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3b. Calculate the drift speed *v* of the electrons in the conductor in cm s^{-1}. State your answer to an appropriate number of significant figures. *[3 marks]*

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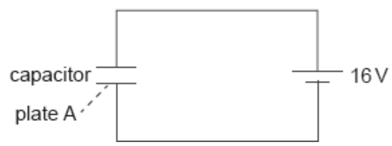
A capacitor consists of two parallel square plates separated by a vacuum. The plates are 2.5 cm × 2.5 cm squares. The capacitance of the capacitor is 4.3 pF.

4a. Calculate the distance between the plates. *[1 mark]*

4b. The capacitor is connected to a 16 V cell as shown. *[2 marks]*

diagram not to scale

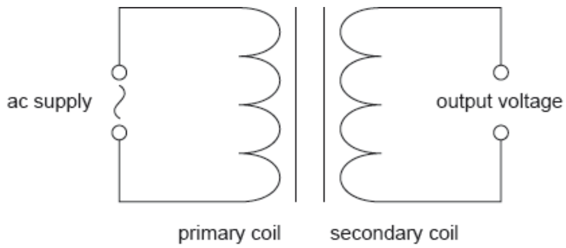


Calculate the magnitude and the sign of the charge on plate A when the capacitor is fully charged.

4c. The capacitor is fully charged and the space between the plates is then filled with a dielectric of permittivity $\varepsilon = 3.0\,\varepsilon_0$. *[2 marks]*

Explain whether the magnitude of the charge on plate A increases, decreases or stays constant.

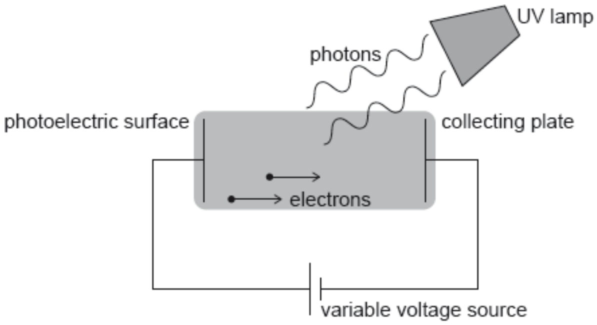
4d. In a different circuit, a transformer is connected to an alternating current (ac) supply. *[3 marks]*



The transformer has 100 turns in the primary coil and 1200 turns in the secondary coil. The peak value of the voltage of the ac supply is 220 V. Determine the root mean square (rms) value of the output voltage.

4e. Describe the use of transformers in electrical power distribution. *[3 marks]*

Hydrogen atoms in an ultraviolet (UV) lamp make transitions from the first excited state to the ground state. Photons are emitted and are incident on a photoelectric surface as shown.



5a. Show that the energy of photons from the UV lamp is about 10 eV. *[2 marks]*

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The photons cause the emission of electrons from the photoelectric surface. The work function of the photoelectric surface is 5.1 eV.

5b. Calculate, in J, the maximum kinetic energy of the emitted electrons. *[2 marks]*

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5c. Suggest, with reference to conservation of energy, how the variable voltage source can be used to stop all emitted electrons from reaching the collecting plate. *[2 marks]*

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5d. The variable voltage can be adjusted so that no electrons reach the collecting plate. Write down the minimum value of the voltage for which no electrons reach the collecting plate. *[1 mark]*

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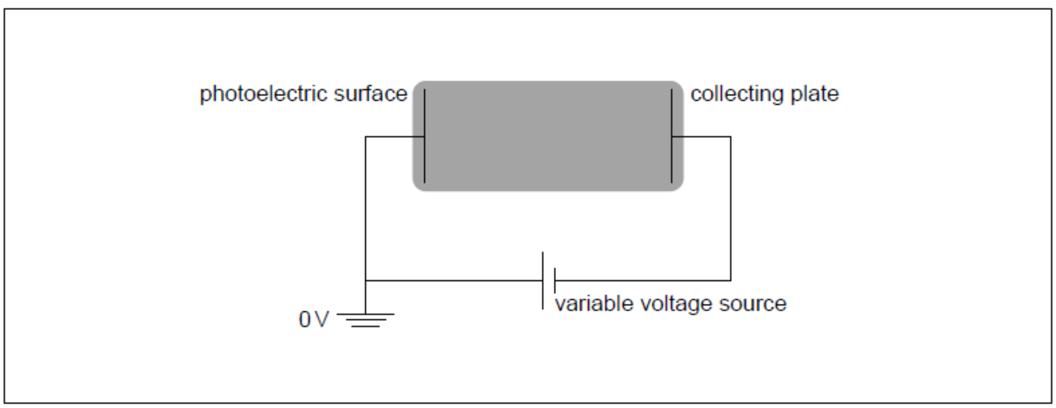
The electric potential of the photoelectric surface is 0 V. The variable voltage is adjusted so that the collecting plate is at –1.2 V.



5e. On the diagram, draw and label the equipotential lines at –0.4 V and –0.8 V. *[2 marks]*

5f. An electron is emitted from the photoelectric surface with kinetic energy 2.1 eV. Calculate the speed of the electron at the collecting plate. *[2 marks]*

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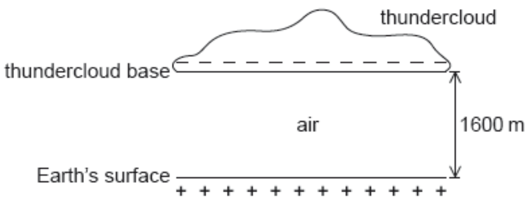
A negatively charged thundercloud above the Earth's surface may be modelled by a parallel plate capacitor.



The lower plate of the capacitor is the Earth's surface and the upper plate is the base of the thundercloud.

The following data are available.

Area of thundercloud base	$= 1.2 \times 10^{8}\ \text{m}^2$
Charge on thundercloud base	$= -25\ \text{C}$
Distance of thundercloud base from Earth's surface	$= 1600\ \text{m}$
Permittivity of air	$= 8.8 \times 10^{-12}\ \text{F m}^{-1}$

6a. Show that the capacitance of this arrangement is $C = 6.6 \times 10^{-7}$ F. *[1 mark]*

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6b. Calculate in V, the potential difference between the thundercloud and the Earth's surface. *[2 marks]*

6c. Calculate in J, the energy stored in the system. *[2 marks]*

Lightning takes place when the capacitor discharges through the air between the thundercloud and the Earth's surface. The time constant of the system is 32 ms. A lightning strike lasts for 18 ms.

6d. Show that about –11 C of charge is delivered to the Earth's surface. *[3 marks]*

6e. Calculate, in A, the average current during the discharge. *[1 mark]*

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6f. State **one** assumption that needs to be made so that the Earth-thundercloud system may be modelled by a parallel plate capacitor. *[1 mark]*

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7a. Bohr modified the Rutherford model by introducing the condition $mvr = n\frac{h}{2\pi}$. Outline the reason for this modification. *[3 marks]*

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7b. Show that the speed v of an electron in the hydrogen atom is related to the radius r of the orbit by the expression *[1 mark]*

$$v = \sqrt{\frac{ke^2}{m_{\mathrm{e}}r}}$$

where k is the Coulomb constant.

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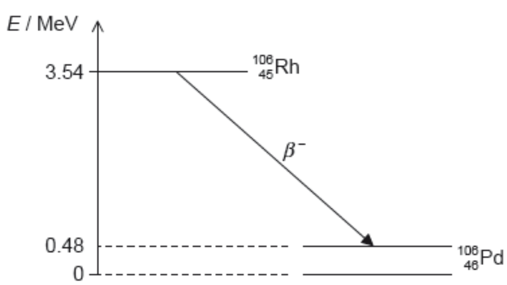
7c. Using the answer in (b) and (c)(i), deduce that the radius *r* of the electron's orbit in the ground state of hydrogen is given by the following expression. *[2 marks]*

$$r = \frac{h^2}{4\pi^2 k m_e e^2}$$

7d. Calculate the electron's orbital radius in (c)(ii). *[1 mark]*

Rhodium-106 ($^{106}_{45}\mathrm{Rh}$) decays into palladium-106 ($^{106}_{46}\mathrm{Pd}$) by beta minus (β^-) decay. The diagram shows some of the nuclear energy levels of rhodium-106 and palladium-106. The arrow represents the β^- decay.



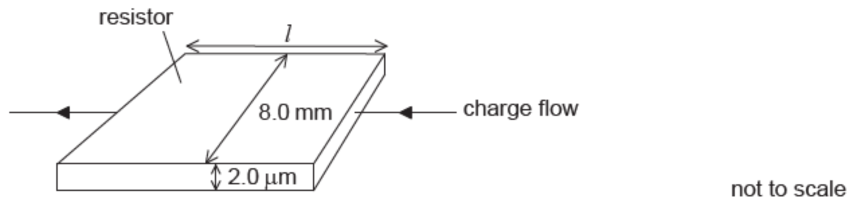
7e. Explain what may be deduced about the energy of the electron in the β^- decay. *[3 marks]*

7f. Suggest why the β^- decay is followed by the emission of a gamma ray photon. *[1 mark]*

7g. Calculate the wavelength of the gamma ray photon in (d)(ii). *[2 marks]*

Electrical resistors can be made by forming a thin film of carbon on a layer of an insulating material.

A carbon film resistor is made from a film of width 8.0 mm and of thickness 2.0 µm. The diagram shows the direction of charge flow through the resistor.

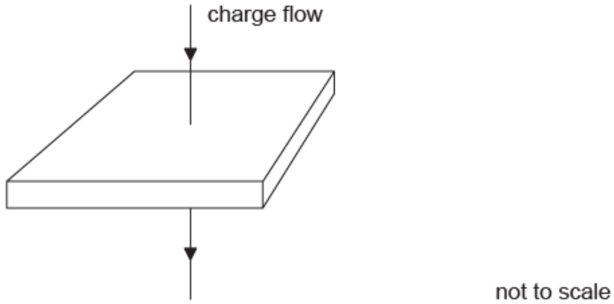


8a. The resistance of the carbon film is 82 Ω. The resistivity of carbon is 4.1×10^{-5} Ω m. Calculate the length *l* of the film. *[1 mark]*

8b. The film must dissipate a power less than 1500 W from each square metre of its surface to avoid damage. Calculate the maximum allowable current for the resistor. *[2 marks]*

8c. State why knowledge of quantities such as resistivity is useful to scientists. *[1 mark]*

8d. The current direction is now changed so that charge flows vertically through the film. *[2 marks]*



Deduce, without calculation, the change in the resistance.

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8e. Draw a circuit diagram to show how you could measure the resistance of the carbon-film resistor using a potential divider arrangement to limit the potential difference across the resistor. *[2 marks]*

A heater in an electric shower has a power of 8.5 kW when connected to a 240 V electrical supply. It is connected to the electrical supply by a copper cable.

The following data are available:

Length of cable = 10 m
Cross-sectional area of cable = 6.0 mm^2
Resistivity of copper = 1.7×10^{-8} Ω m

9a. Calculate the current in the copper cable. *[1 mark]*

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9b. Calculate the resistance of the cable. *[2 marks]*

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9c. Explain, in terms of electrons, what happens to the resistance of the cable as the temperature of the cable increases. *[3 marks]*

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9d. The heater changes the temperature of the water by 35 K. The specific heat capacity of water is 4200 J kg^{-1} K^{-1}. *[4 marks]*

Determine the rate at which water flows through the shower. State an appropriate unit for your answer.

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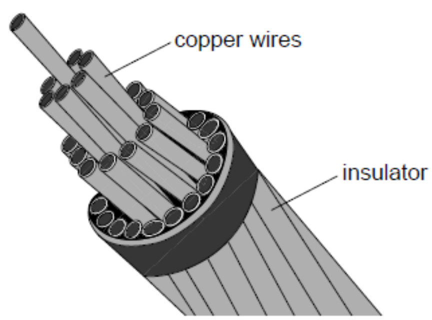
A cable consisting of many copper wires is used to transfer electrical energy from a generator to an electrical load. The copper wires are protected by an insulator.



10a. The copper wires and insulator are both exposed to an electric field. Discuss, with reference to charge carriers, why there is a significant electric current only in the copper wires. *[3 marks]*

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The cable consists of 32 copper wires each of length 35 km. Each wire has a resistance of 64 Ω. The resistivity of copper is 1.7×10^{-8} Ω m.

10b. Calculate the radius of each **wire**. *[2 marks]*

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10c. There is a current of 730 A in the cable. Show that the power loss in 1 m of the cable is about 30 W. *[2 marks]*

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10d. When the current is switched on in the cable the initial rate of rise of temperature of the cable is 35 mK s^{-1}. The specific heat capacity of copper is 390 J kg^{-1} K^{-1}. Determine the mass of a length of one metre of the cable. *[2 marks]*

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11. Calculate the power dissipated in the cable. *[2 marks]*

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12a. State Faraday's law of induction. *[2 marks]*

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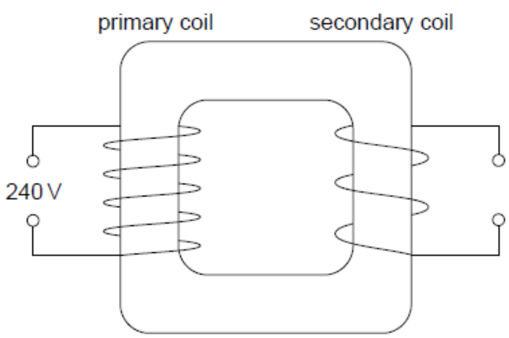
The diagram shows a sketch of an ideal step-down transformer.



The number of turns in the primary coil is 1800 and that in the secondary coil is 90.

12b. Explain, using Faraday's law of induction, how the transformer steps down the voltage. *[4 marks]*

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12c. The input voltage is 240 V. Calculate the output voltage. *[2 marks]*

12d. Outline how energy losses are reduced in the core of a practical transformer. *[2 marks]*

12e. Step-up transformers are used in power stations to increase the voltage at which the electricity is transmitted. Explain why this is done. *[2 marks]*

The following data are available for a natural gas power station that has a high efficiency.

Rate of consumption of natural gas	= 14.6 kg s^{-1}
Specific energy of natural gas	= 55.5 MJ kg^{-1}
Efficiency of electrical power generation	= 59.0 %
Mass of CO_2 generated per kg of natural gas	= 2.75 kg
One year	= 3.16×10^7 s

13a. Electrical power output is produced by several alternating current (ac) generators which use transformers to deliver energy to the national electricity grid. *[4 marks]*

The following data are available. Root mean square (rms) values are given.

ac generator output voltage to a transformer = 25 kV ac generator output current to a transformer = 3.9 kA Transformer output voltage to the grid = 330 kV Transformer efficiency = 96%

(i) Calculate the current output by the transformer to the grid. Give your answer to an appropriate number of significant figures.

(ii) Electrical energy is often delivered across large distances at 330 kV. Identify the main advantage of using this very high potential difference.

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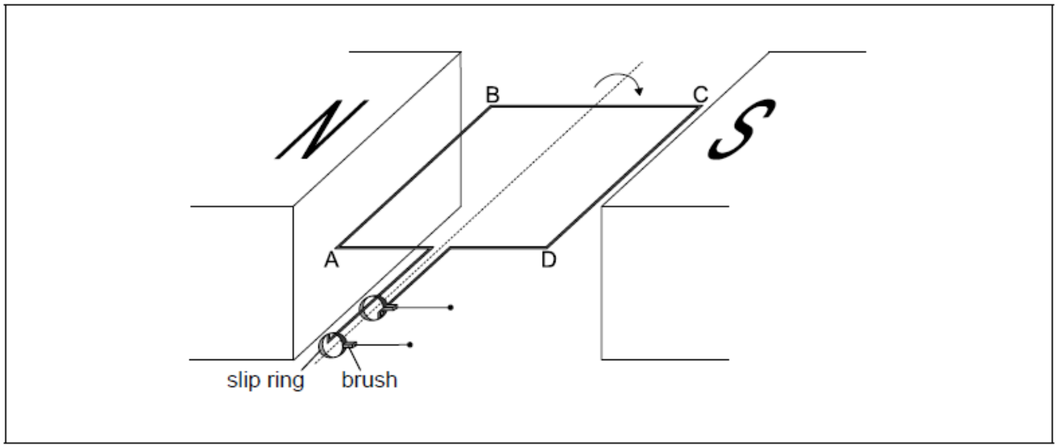
13b. In an alternating current (ac) generator, a square coil ABCD rotates in a magnetic field. *[5 marks]*



The ends of the coil are connected to slip rings and brushes. The plane of the coil is shown at the instant when it is parallel to the magnetic field. Only one coil is shown for clarity.

The following data are available.

Dimensions of the coil = 8.5 cm×8.5 cm Number of turns on the coil = 80 Speed of edge AB = 2.0 ms^{-1} Uniform magnetic field strength = 0.34 T

(i) Explain, with reference to the diagram, how the rotation of the generator produces an electromotive force (emf) between the brushes.

(ii) Calculate, for the position in the diagram, the magnitude of the instantaneous emf generated by a **single** wire between A and B of the coil.

(iii) Hence, calculate the total instantaneous peak emf between the brushes.

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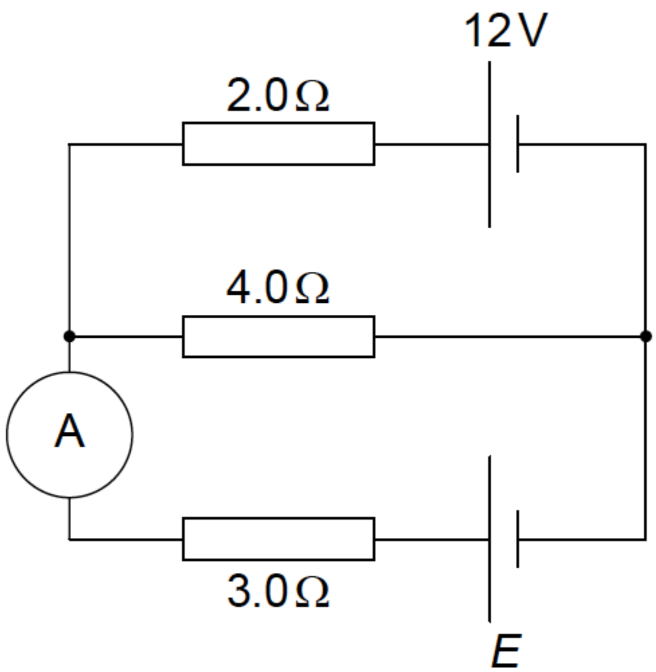
14a. Two cells of negligible internal resistance are connected in a circuit. *[2 marks]*



The top cell has electromotive force (emf) 12V. The emf of the lower cell is unknown. The ideal ammeter reads zero current.

Calculate the emf *E* of the lower cell.

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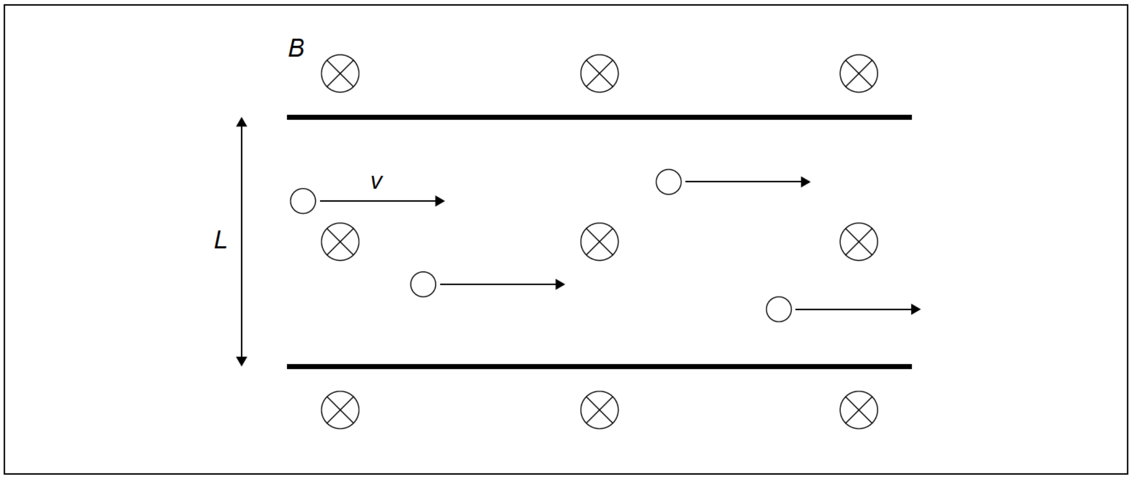
14b. The diagram shows charge carriers moving with speed v in a metallic conductor of width L. The conductor is exposed to a uniform magnetic field B that is directed into the page. *[3 marks]*



(i) Show that the potential difference V that is established across the conductor is given by $V=vBL$.

(ii) On the diagram, label the part of the conductor where negative charge accumulates.

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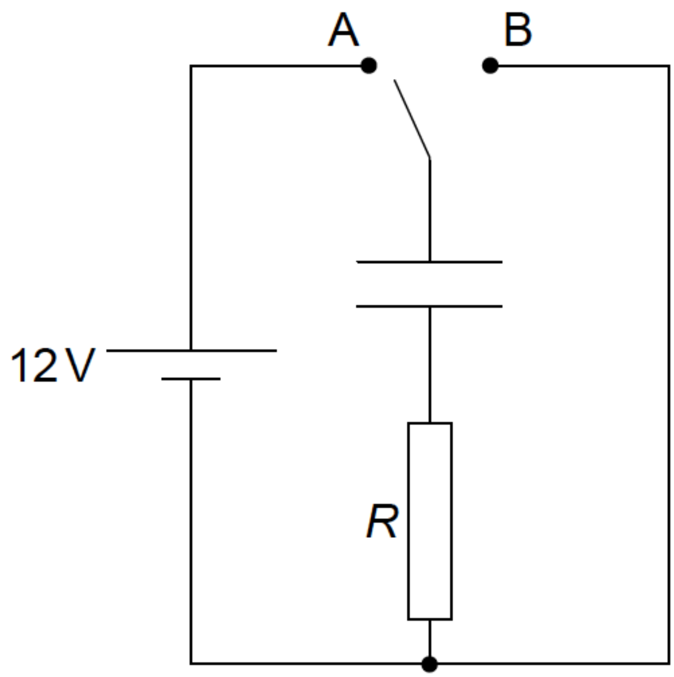
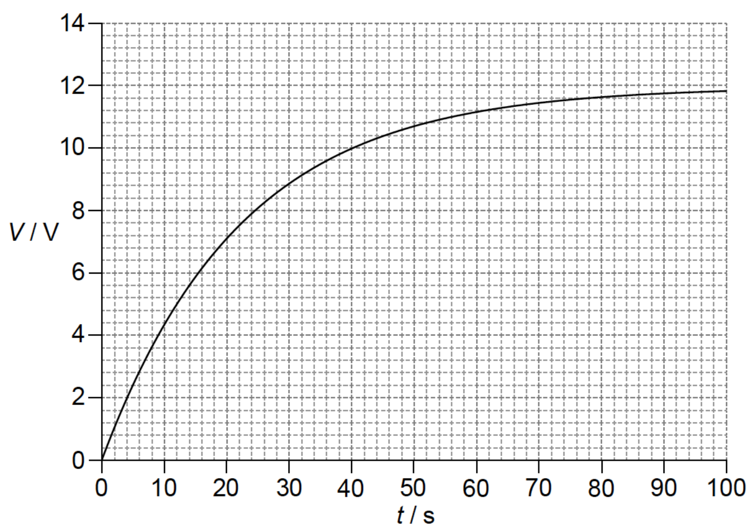
An uncharged capacitor in a vacuum is connected to a cell of emf 12V and negligible internal resistance. A resistor of resistance R is also connected.



At t=0 the switch is placed at position A. The graph shows the variation with time t of the voltage V across the capacitor. The capacitor has capacitance 4.5µF in a vacuum.



15a. On the axes, draw a graph to show the variation with time of the voltage across the resistor. *[2 marks]*

15b. (i) The time constant of this circuit is 22s. State what is meant by the time constant. *[2 marks]*

(ii) Calculate the resistance *R*.

15c. A dielectric material is now inserted between the plates of the fully charged capacitor. State the effect, if any, on *[2 marks]*

(i) the potential difference across the capacitor.

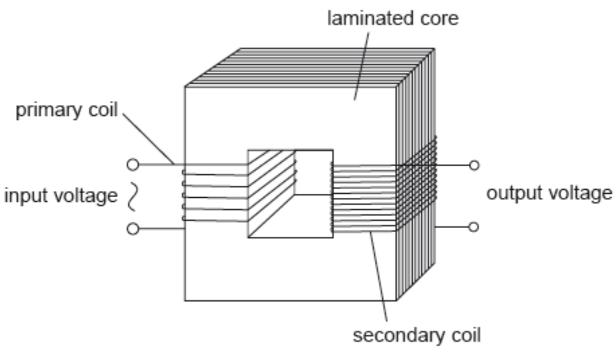
(ii) the charge on one of the capacitor plates.

15d. (i) The permittivity of the dielectric material in (c) is twice that of a vacuum. Calculate the energy stored in the capacitor when it is fully charged. *[3 marks]*

(ii) The switch in the circuit is now moved to position B and the fully charged capacitor discharges. Describe what happens to the energy in (d)(i).

Part 2 Power transmissions

The diagram shows the main features of an ideal transformer whose primary coil is connected to a source of alternating current (ac) voltage.



16a. Outline, with reference to electromagnetic induction, how a voltage is induced across the secondary coil. *[3 marks]*

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16b. The primary coil has 25 turns and is connected to an alternating supply with an input voltage of root mean squared (rms) value 12 V. The secondary coil has 80 turns and is not connected to an external circuit. Determine the peak voltage induced across the secondary coil. *[2 marks]*

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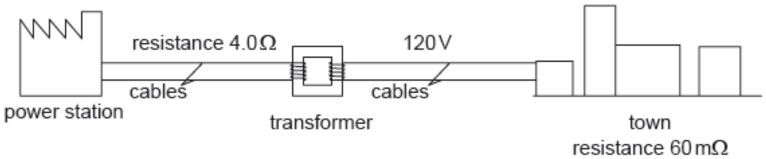
A different transformer is used to transmit power to a small town.



The transmission cables from the power station to the transformer have a total resistance of 4.0 Ω. The transformer is 90% efficient and steps down the voltage to 120 V. At the time of maximum power demand the effective resistance of the town and of the cables from the transformer to the town is 60 mΩ.

16c. Calculate the current in the cables connected to the town *[1 mark]*

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16d. Calculate the power supplied to the transformer. *[2 marks]*

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16e. Determine the input voltage to the transformer if the power loss in the cables from the power station is 2.0 kW. *[2 marks]*

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16f. Outline why laminating the core improves the efficiency of a transformer. *[2 marks]*

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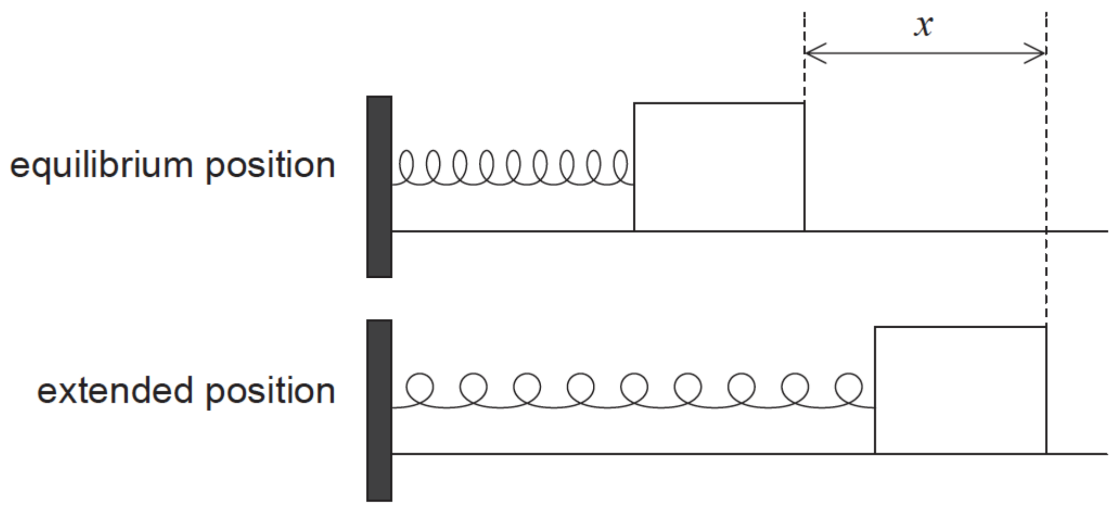
This question is in two parts. **Part 1** is about simple harmonic motion (SHM). **Part 2** is about current electricity.

Part 1 Simple harmonic motion (SHM)

An object is placed on a frictionless surface. The object is attached by a spring fixed at one end and oscillates at the end of the spring with simple harmonic motion (SHM).



The tension F in the spring is given by $F = k\,x$ where x is the extension of the spring and k is a constant.

17a. Show that $\omega^2 = \frac{k}{m}$. *[2 marks]*

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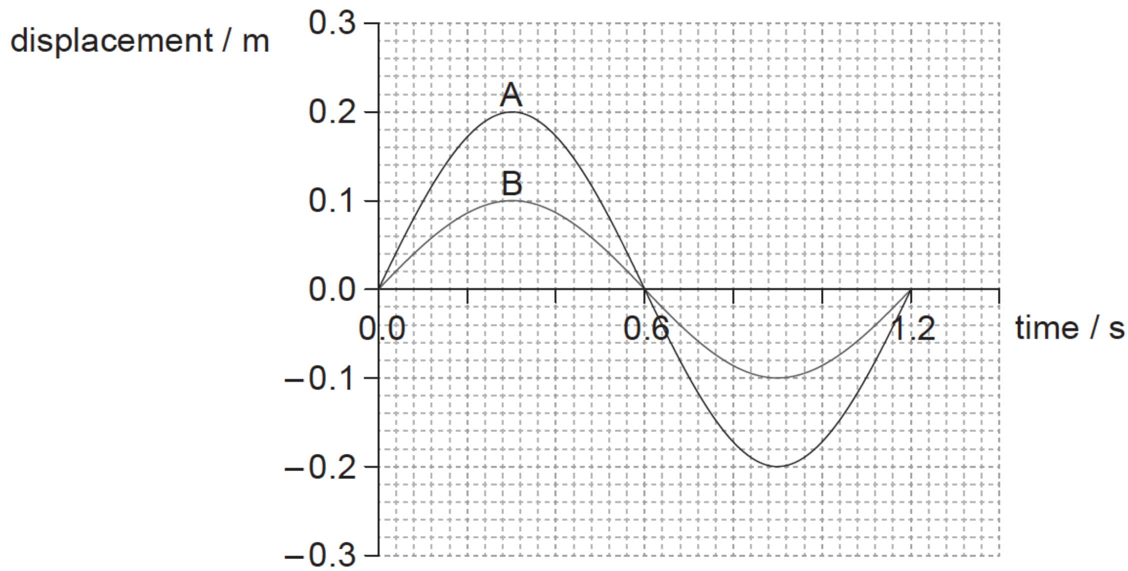
17b. One cycle of the variation of displacement with time is shown for two separate mass–spring systems, A and B. *[3 marks]*



(i) Calculate the frequency of the oscillation of A.

(ii) The springs used in A and B are identical. Show that the mass in A is equal to the mass in B.

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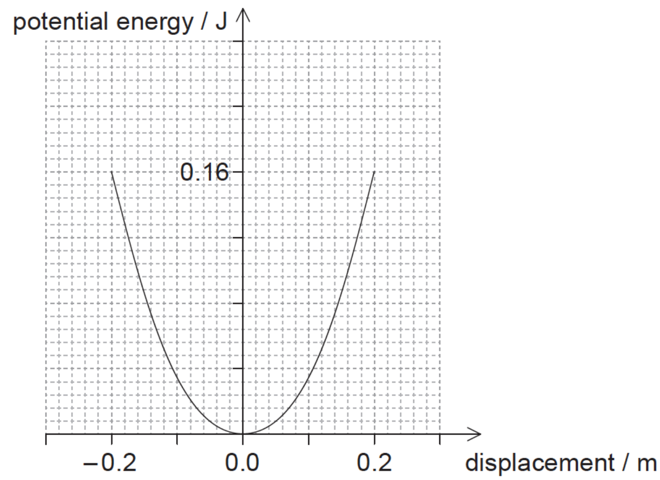
17c. The graph shows the variation of the potential energy of A with displacement. *[5 marks]*



On the axes,

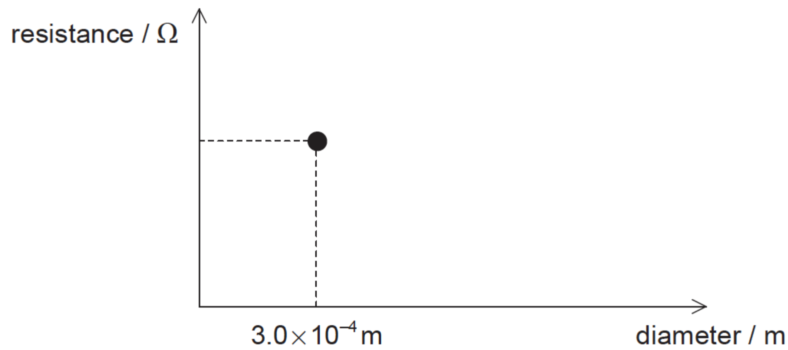
(i) draw a graph to show the variation of kinetic energy with displacement for the mass in A. Label this A.

(ii) sketch a graph to show the variation of kinetic energy with displacement for the mass in B. Label this B.

17d. A 24 Ω resistor is made from a conducting wire. *[4 marks]*

(i) The diameter of the wire is 0.30 mm and the wire has a resistivity of 1.7×10^{-8} Ωm. Calculate the length of the wire.

(ii) On the axes, draw a graph to show how the resistance of the wire in (d)(i) varies with the diameter of the wire when the length is constant. The data point for the diameter of 0.30 mm has already been plotted for you.



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17e. The 24 Ω resistor is covered in an insulating material. Explain the reasons for the differences between the electrical properties of the insulating material and the electrical properties of the wire. *[3 marks]*

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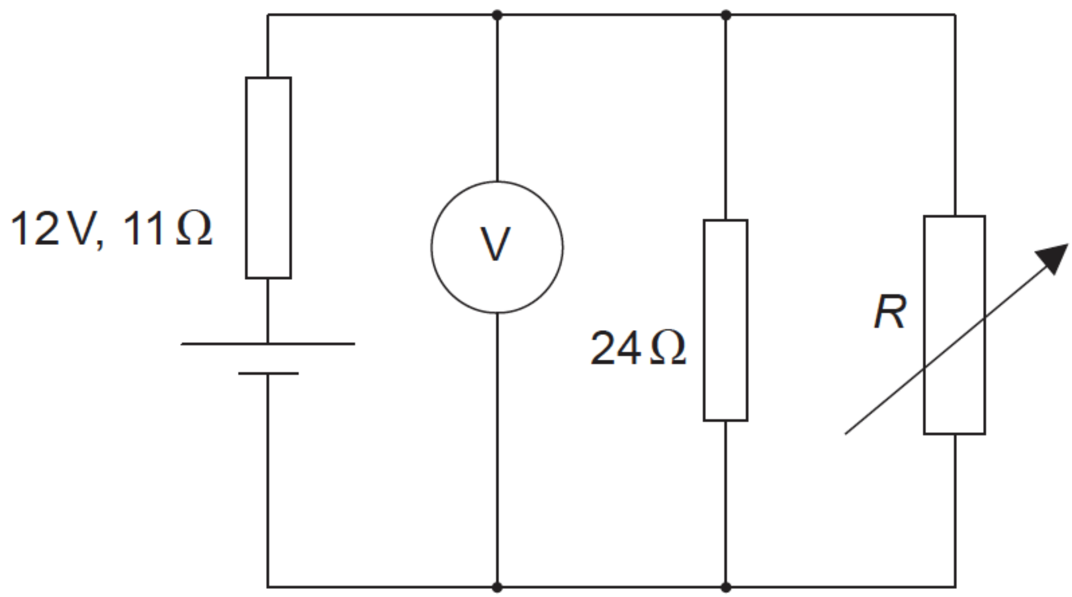
17f. An electric circuit consists of a supply connected to a 24Ω resistor in parallel with a variable resistor of resistance *R*. The supply has an emf of 12V and an internal resistance of 11Ω. *[8 marks]*



Power supplies deliver maximum power to an external circuit when the resistance of the external circuit equals the internal resistance of the power supply.

(i) Determine the value of *R* for this circuit at which maximum power is delivered to the external circuit.

(ii) Calculate the reading on the voltmeter for the value of *R* you determined in (f)(i).

(iii) Calculate the total power dissipated in the circuit when the maximum power is being delivered to the external circuit.

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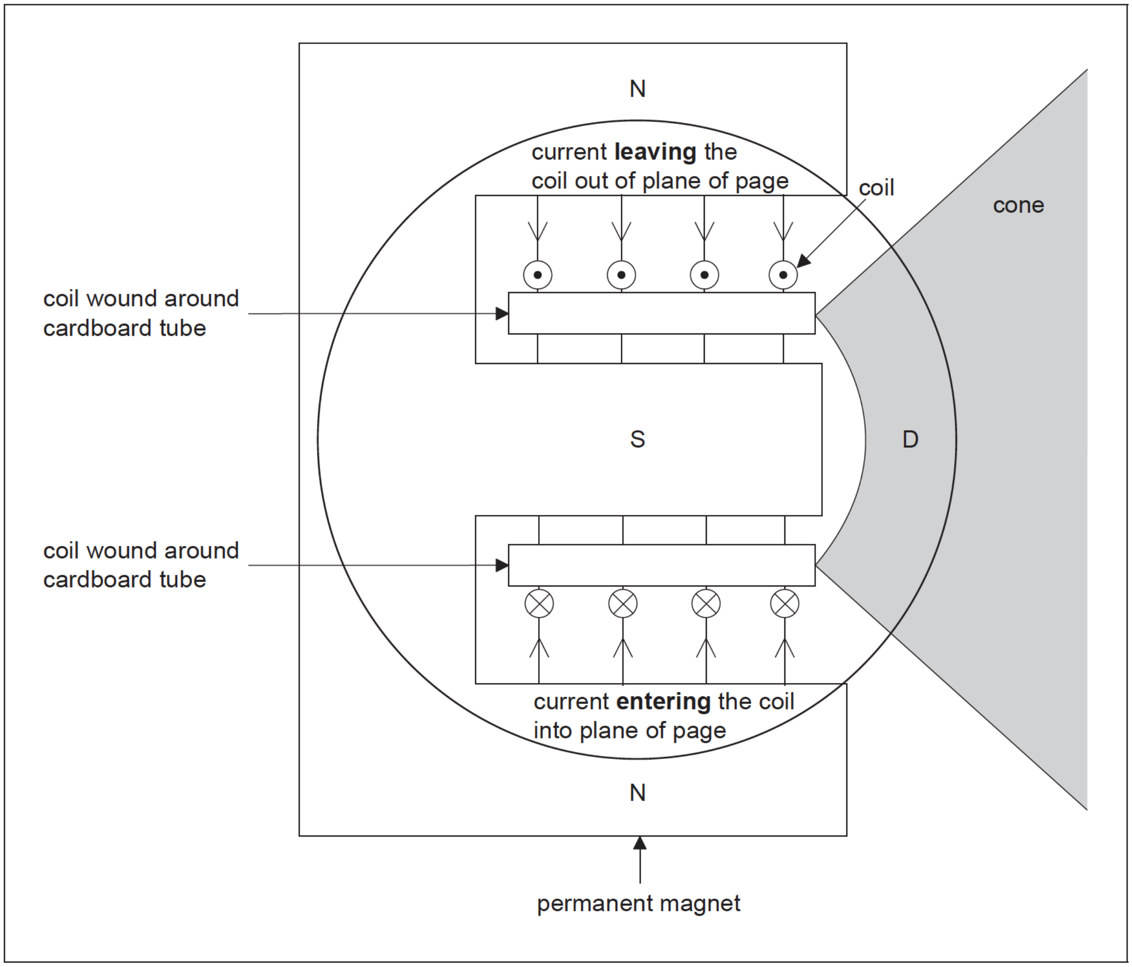
This question is in two parts. **Part 1** is about the electrical and magnetic characteristics of a loudspeaker. **Part 2** is about vibrations and waves.

Part 1 Electrical and magnetic characteristics of a loudspeaker

The diagram shows the main features of a loudspeaker L. A current-carrying coil is positioned within the magnetic field provided by a permanent magnet. The diagram also shows the directions of the magnetic field and of the current in the coil at a particular instant. The dust cap D prevents dust from blocking the gap between the cardboard tube and the south pole of the magnet.



The coil consists of 150 turns, each of average diameter 2.5 cm. The magnetic field of the permanent magnet has strength 0.40 mT. The peak current in the coil is 0.45 mA.

18a. Identify, **on the diagram**, the direction of the force on the coil with the current directions shown. *[2 marks]*

18b. Calculate the maximum magnetic force acting on the coil. *[3 marks]*

18c. Explain, with reference to electromagnetic induction, the effect of the motion of the coil on the current. *[3 marks]*

This question is in **two** parts. **Part 1** is about the motion of a car. **Part 2** is about electricity.

Part 1 Motion of a car

19a. A car accelerates uniformly along a straight horizontal road from an initial speed of $12\ \mathrm{m\,s^{-1}}$ to a final speed of $28\ \mathrm{m\,s^{-1}}$ in a distance of 250 m. The mass of the car is 1200 kg. Determine the rate at which the engine is supplying kinetic energy to the car as it accelerates. *[4 marks]*

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A car is travelling along the straight horizontal road at its maximum speed of $56\ \mathrm{m\,s^{-1}}$. The power output required at the wheels is 0.13 MW.

19b. A car is travelling along a straight horizontal road at its maximum speed of $56\ \mathrm{m\,s^{-1}}$. *[5 marks]*
The power output required at the wheels is 0.13 MW.

(i) Calculate the total resistive force acting on the car when it is travelling at a constant speed of $56\ \mathrm{m\,s^{-1}}$.

(ii) The mass of the car is 1200 kg. The resistive force F is related to the speed v by $F \propto v^2$. Using your answer to (b)(i), determine the maximum theoretical acceleration of the car at a speed of $28\ \mathrm{m\,s^{-1}}$.

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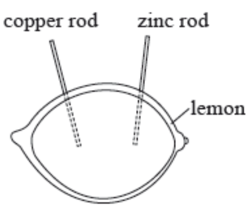
A driver moves the car in a horizontal circular path of radius 200 m. Each of the four tyres will not grip the road if the frictional force between a tyre and the road becomes less than 1500 N.

19c. (i) Calculate the maximum speed of the car at which it can continue to move in the circular path. Assume that the radius of the path is the same for each tyre. *[6 marks]*

(ii) While the car is travelling around the circle, the people in the car have the sensation that they are being thrown outwards. Outline how Newton’s first law of motion accounts for this sensation.

Part 2 Electricity

A lemon can be used to make an electric cell by pushing a copper rod and a zinc rod into the lemon.



A student constructs a lemon cell and connects it in an electrical circuit with a variable resistor. The student measures the potential difference V across the lemon and the current I in the lemon.

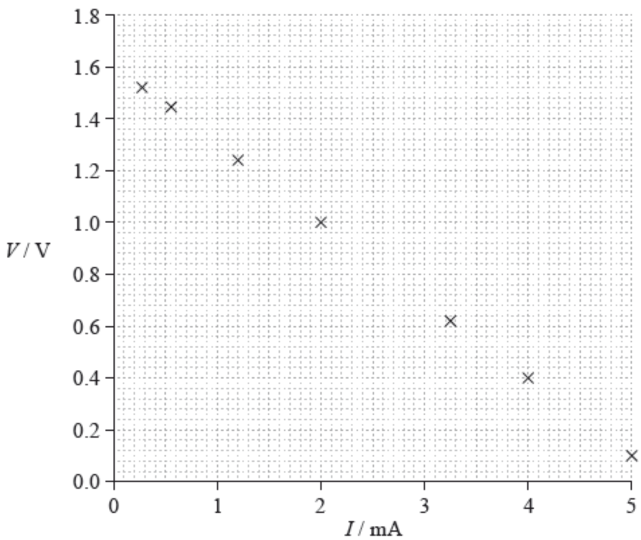
19d. (i) Draw a circuit diagram of the experimental arrangement that will enable the student to collect the data for the graph. *[10 marks]*

(ii) Show that the potential difference V across the lemon is given by

$$V = E - Ir$$

where E is the emf of the lemon cell and r is the internal resistance of the lemon cell.

(iii) The graph shows how V varies with I.



Using the graph, estimate the emf of the lemon cell.

(iv) Determine the internal resistance of the lemon cell.

(v) The lemon cell is used to supply energy to a digital clock that requires a current of $6.0\ \mu\mathrm{A}$. The clock runs for 16 hours. Calculate the charge that flows through the clock in this time.

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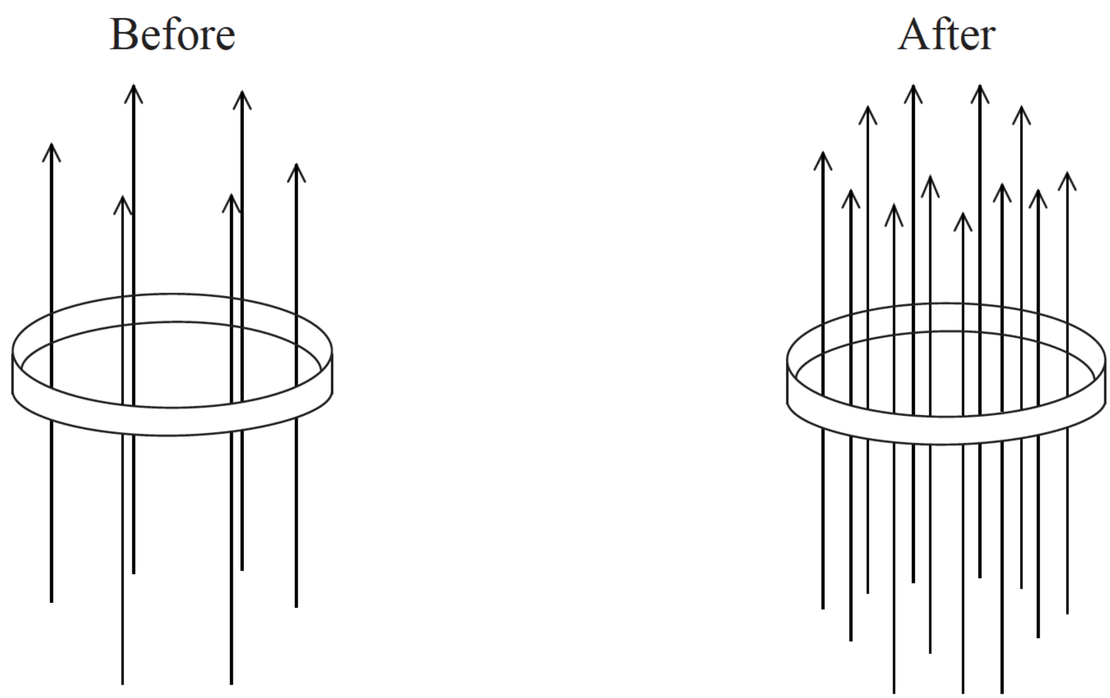
This question is about electromagnetic induction.

A metal ring is placed in a magnetic field which is directed upwards. The magnetic flux through the ring increases over a time interval.



20a. State and explain the direction of the current induced in the ring during this change. *[3 marks]*

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20b. The following data are available. *[3 marks]*

Resistance of ring = $3.0\times10^{-3}\Omega$
Initial magnetic flux = 1.2×10^{-5}Wb
Final magnetic flux = 2.4×10^{-5}Wb
Time interval = 2.0×10^{-3}s

Calculate the average current induced in the ring.

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