EXAMPLE GRAMMAR SCHOOL

ESAT Mock: Worked Solutions

Physics

Paper SMP-2026-09 · Version 1.0

Staff copy

This document contains the answers. Keep it away from candidates until the paper has been sat. Marking guidance is in the separate mark scheme.

Question 1

P7.1 · Radioactivity · ★★★☆☆ · 90 s

A textbook claims that virtually all of an atom's mass sits in its tiny central nucleus, and a student decides to check that claim numerically for the single neutral atom shown in the diagram. Treat the atom's mass as the sum of the masses of its individual particles. To a good approximation, what fraction of the atom's total mass is carried by its electrons?

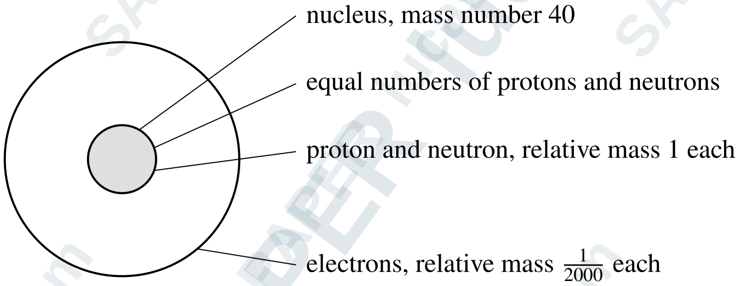


diagram not to scale

- **A.** $\frac{1}{2000}$
- **B.** $\frac{1}{8000}$
- **C.** $\frac{1}{6000}$
- **D.** $\frac{1}{400}$
- **E.** $\frac{1}{100}$
- **F.** $\frac{1}{4000}$
- **G.** $\frac{1}{40000}$
- **H.** $\frac{1}{80000}$

Answer F. Key idea

On the relative mass scale a proton and a neutron each count as 1, so the mass number is also the relative mass of the nucleus. An electron is lighter than either by a factor of about two thousand, so although a neutral atom has as many electrons as protons, those electrons contribute a share of the mass smaller by that same factor. Comparing the two totals means counting the particles of each type first, weighting each count by its relative mass, and only then forming the ratio.

Worked solution

1. Count the three kinds of particle

The mass number counts nucleons only, and the protons and neutrons are equal in number, so

$$p = n = \frac{40}{2} = 20$$

The atom is neutral, so it carries one electron for every proton, giving 20 electrons.

2. Add up the mass held in the nucleus

A proton and a neutron each have relative mass 1, so the 40 nucleons contribute

$$20 \times 1 + 20 \times 1 = 40$$

3. Add up the mass held by the electrons

Each electron has relative mass $\frac{1}{2000}$, so the twenty of them contribute

$$20 \times \frac{1}{2000} = \frac{1}{100} = 0.01$$

4. Form the fraction and check it

$$\frac{0.01}{40 + 0.01} = \frac{0.01}{40.01} = \frac{1}{4001} \approx \frac{1}{4000}$$

Sanity check: the nucleons outnumber the electrons only two to one, while each electron is two thousand times lighter than a nucleon, so the answer should be about $\frac{1}{2} \times \frac{1}{2000}$. Whether the 0.01 is kept in the denominator or dropped makes no difference at this precision, which is the point of the claim being tested: the electrons are a rounding error in the mass of an atom.

Matches Option **F**.

Why the other options are wrong

- **A** ($\frac{1}{2000}$): The neutrons were left out of the atom's mass, so the nucleus was given a relative mass of 20 rather than 40, and the fraction came out as $\frac{0.01}{20} = \frac{1}{2000}$. Neutrons carry no charge but they carry the same relative mass as protons, and here they supply half the 40 mass units. *(Neutron mass omitted from the nucleus)*
- **B** ($\frac{1}{8000}$): Halved 40 to get 20 protons and 20 neutrons, then halved again on the way to the electrons and used 10 of them: $10 \times \frac{1}{2000} = \frac{1}{200}$, and $\frac{1}{200} \div 40 = \frac{1}{8000}$. A neutral atom carries one electron for every proton, and there are 20 protons here, so the electron count is 20. *(Mass number halved a second time)*
- **C** ($\frac{1}{6000}$): The electron mass $\frac{1}{100}$ was divided by the number of particles in the atom, $20 + 20 + 20 = 60$, giving $\frac{1}{6000}$. The denominator must be a relative mass, not a head count: the twenty electrons add only 0.01 to it, not twenty units. *(Particle count used in place of relative mass)*
- **D** ($\frac{1}{400}$): Reached $\frac{0.01}{40}$ correctly and then divided by 4 rather than by 40, which is the same as placing the decimal point one column late: $0.01 \div 40 = 0.00025 = \frac{1}{4000}$, whereas $0.0025 = \frac{1}{400}$. The atom's relative mass is 40, not 4. *(Decimal place lost in the final division)*
- **E** ($\frac{1}{100}$): The total relative mass of the electrons, $20 \times \frac{1}{2000} = \frac{1}{100}$, was quoted as the answer without ever being divided by the mass of the whole atom. That figure is a mass on the relative scale, not a share of the atom's mass, and dividing it by 40 is the step that turns it into one. *(Electron mass not expressed as a fraction)*
- **G** ($\frac{1}{40000}$): Cancelled $20 \times \frac{1}{2000}$ to $\frac{1}{1000}$ instead of $\frac{1}{100}$, losing a factor of ten, then divided by the atom's relative mass: $\frac{1}{1000} \div 40 = \frac{1}{40000}$. Since $2000 \div 20 = 100$, the twenty electrons together weigh $\frac{1}{100}$. *(Cancelling slip in the electron total)*

- **H** ($\frac{1}{80000}$): Only a single electron was weighed, giving $\frac{1}{2000} \div 40 = \frac{1}{80000}$. A neutral atom holds one electron for every proton, so there are twenty of them here and the numerator must be twenty times as large. *(One electron used instead of all twenty)*

Common mistake. Building the atom's mass out of the protons alone, dividing 0.01 by 20 and answering $\frac{1}{2000}$. The neutron has no charge, which makes it easy to forget, but on the relative mass scale it weighs the same as a proton, so half of the 40 mass units in this atom are neutrons. Charge and mass are separate properties and the neutron is only absent from one of them.

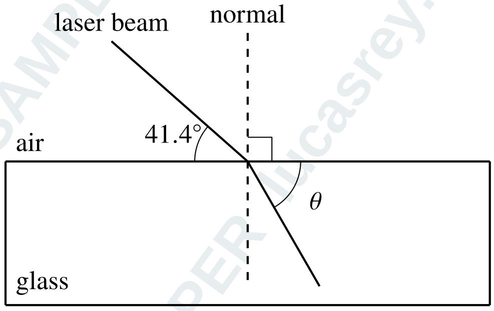
Takeaway. The Cheat Code: weight before you count. Write down how many protons, neutrons and electrons there are, multiply each count by its relative mass (1, 1 and $\frac{1}{2000}$), and let the mass number stand in for the whole nucleus rather than adding nucleons one at a time.

Time-saving tip. Speed Heuristic: with equal protons and neutrons the electron count is half the mass number, so the electron mass is $\frac{A}{2} \times \frac{1}{2000} = \frac{A}{4000}$ against a nuclear mass of A. The A cancels and the answer is $\frac{1}{4000}$ whatever the mass number is, so you never need the 40 at all.

Question 2

P6.3 · Waves · ★★★☆☆ · 90 s

An optical technician sets a rectangular crown glass block on a bench with its top face horizontal. The block is known to bend a beam arriving at 30° to the normal into a path 19.5° from the normal inside the glass. She now aims her laser at the same face as shown, and the refracted beam inside the glass makes an angle θ with the face. Take $\sin 19.5° = 0.33$ and $\sin 48.6° = 0.75$. What is θ?



A. 70.5°
B. 60.0°
C. 57.6°
D. 41.4°
E. 30.0°

Answer B. Key idea

Refraction at a plane boundary obeys $n = \dfrac{\sin i}{\sin r}$, in which both angles are measured from the normal, the line drawn perpendicular to the surface. One measured pair of angles fixes n for that boundary, and the same n then sets the refracted direction for any other angle of incidence at that boundary. An angle given from the surface has to be turned into an angle from the normal by subtracting it from 90°, and turned back the same way when the answer is wanted from the surface.

Worked solution

Step 1: Read the angle of incidence from the diagram

The beam is marked at 41.4° to the face, but refraction is worked from the normal, drawn perpendicular to that face. The angle of incidence is therefore $i = 90° - 41.4° = 48.6°$.

Step 2: Get the refractive index from the check ray

The check ray crosses the same face at 30° to the normal and runs at 19.5° to the normal inside the glass, so $n = \dfrac{\sin 30°}{\sin 19.5°} = \dfrac{0.50}{0.33} = 1.5$ to two significant figures, a value typical of crown glass.

Step 3: Refract the laser beam

The same n governs every ray crossing this boundary, so $\sin r = \dfrac{\sin i}{n} = \dfrac{0.75}{1.5} = 0.50$, giving $r = 30°$ measured from the normal.

Step 4: Convert to the angle asked for

θ is the angle to the face, not to the normal, so $\theta = 90° - 30° = 60.0°$.

Sanity check: the beam arrives 48.6° from the normal and continues at 30° from it, so it has bent towards the normal on entering the glass, which is the direction expected for light passing from air into a denser medium. It is bent through 18.6° against the check ray's 10.5°, and the larger bend belongs to the larger angle of incidence.

Matches Option **B**.

Why the other options are wrong

- A (70.5°): This carries the check ray's path over to the laser beam, keeping $r = 19.5°$ from the normal and converting it to the face: $90° - 19.5° = 70.5°$. The refracted angle is not a fixed property of the glass; only n is, and here the beam arrives at 48.6° rather than 30°. *(Conceptual Error)*
- C (57.6°): This divides the angle instead of its sine: $48.6° \div 1.5 = 32.4°$, then $90° - 32.4° = 57.6°$. Snell's law relates the sines, so the division to make is $\sin r = 0.75 \div 1.5$. *(Misapplied Formula)*
- D (41.4°): This treats the boundary as a mirror and applies angle of incidence = angle of reflection to the beam that crosses it, leaving the angle to the face unchanged at $90° - 48.6° = 41.4°$. Equal angles hold for the part of the light reflected back into the air, not for the part refracted into the glass. *(Conceptual Error)*
- E (30.0°): This is r itself, measured from the normal: $\sin r = 0.75 \div 1.5 = 0.50$ gives $r = 30°$. The diagram marks θ between the refracted beam and the face, which is $90° - 30°$. *(Misread the Question)*

Common mistake. Stopping at the angle measured from the normal. Snell's law returns $r = 30°$, but the diagram marks θ between the refracted beam and the face, so the final $90° - 30°$ is still owed.

Takeaway. The Cheat Code: Every angle in $n = \sin i / \sin r$ is measured from the normal. When a ray diagram marks an angle to the surface instead, subtract it from 90° on the way in, and subtract from 90° again on the way out whenever the answer is wanted from the surface.

Time-saving tip. Speed Heuristic: Stay in sines and never write n as a decimal. Here $0.50 \div 0.33$ sits close to $3/2$, and 0.75 is exactly $3/2 \times 0.50$, so the refracted ray is at 30° to the normal and only $90 - 30$ is left to do.

Question 3

P5.4 · Matter · ★★★☆☆ · 90 s

A soft drink is made by stirring sugar syrup of density 1200 kg m^{-3} into water of density 1000 kg m^{-3}. A sealed carton holds 1.05 kg of the finished drink, and the drink's density is 1050 kg m^{-3}. Assume the two liquids mix without any change in total volume and that the carton itself has negligible mass. What volume of syrup does the carton contain?

A. 350 cm^3
B. 250 cm^3
C. 750 cm^3
D. 1000 cm^3
E. 300 cm^3
F. 500 cm^3
G. 50 cm^3
H. 875 cm^3

Answer B. Key idea

Density is a mass divided by a volume, so a mixture can only be handled through its total mass and its total volume: the two ingredient densities cannot be combined directly. When the volumes simply add, every cubic centimetre of the mixture belongs to one liquid or the other, and the total mass is the sum of what each contributes. Comparing the mixture's mass with the mass the same volume of the lighter liquid alone would have shows how much extra mass the denser liquid brought, and dividing that surplus by the difference in densities gives its volume.

Worked solution

1. Volume of drink in the carton

$\rho = \dfrac{m}{V}$, so $V = \dfrac{m}{\rho} = \dfrac{1.05}{1050} = 1.0 \times 10^{-3}\ \text{m}^3 = 1000\ \text{cm}^3$.

2. Move to convenient units

$1200\ \text{kg m}^{-3} = 1.2\ \text{g cm}^{-3}$, $1000\ \text{kg m}^{-3} = 1.0\ \text{g cm}^{-3}$, and the drink is $1.05\ \text{g cm}^{-3}$. The carton therefore holds $1000 \times 1.05 = 1050$ g of drink.

3. Account for the extra mass

If the carton held nothing but water it would hold 1000 g. The syrup is responsible for the surplus of 50 g, and each 1 cm^3 of syrup that takes the place of 1 cm^3 of water adds $1.2 - 1.0 = 0.2$ g. Hence

$V_{\text{syrup}} = \dfrac{50}{0.2} = 250\ \text{cm}^3$.

4. Rebuild the mixture as a check

250 cm^3 of syrup and 750 cm^3 of water have mass $250 \times 1.2 + 750 \times 1.0 = 300 + 750 = 1050$ g in 1000 cm^3, a density of $1.05\ \text{g cm}^{-3}$ as stated. Notice that 1050 sits a quarter of the way from 1000 to 1200, and the syrup is a quarter of the volume.

Matches Option **B**.

Why the other options are wrong

- **A** (350 cm^3): Read the 1.05 kg as the mass of the water, giving 1050 cm^3 of it, then solved $\dfrac{1050 + 1.2V}{1050 + V} = 1.05$ for the syrup: $1050 + 1.2V = 1102.5 + 1.05V$, so $0.15V = 52.5$ and $V = 350\ \text{cm}^3$. The stated mass belongs to the finished drink, which fixes the carton at 1000 cm^3 before any splitting. *(Stated mass assigned to the water)*
- **C** (750 cm^3): Found the syrup correctly as 250 cm^3 and then quoted what was left over, $1000 - 250 = 750\ \text{cm}^3$, which is the volume of water rather than of syrup. *(Answered the complement)*
- **D** (1000 cm^3): Divided the 50 g surplus by $1.05 - 1.00 = 0.05\ \text{g cm}^{-3}$ instead of by $1.20 - 1.00 = 0.20\ \text{g cm}^{-3}$: $\dfrac{50}{0.05} = 1000\ \text{cm}^3$. The difference that matters is the one between the two liquids, since that is what each cubic centimetre of syrup gains over the water it displaces, and 1000 cm^3 is the whole carton with no water left in it. *(Wrong density difference used)*
- **E** (300 cm^3): Found the mass of syrup, $250 \times 1.2 = 300$ g, and read that number straight off as a volume in cm^3. That step is only valid for a liquid of density $1.0\ \text{g cm}^{-3}$, which the syrup is not. *(Mass read as a volume)*
- **F** (500 cm^3): Split the carton in half on the assumption that a mixture always lies midway between its ingredients. Half of each would give $\dfrac{1200 + 1000}{2} = 1100\ \text{kg m}^{-3}$, which is not the density the carton is stated to have. *(Assumed equal volumes)*
- **G** (50 cm^3): Divided the surplus 50 g by water's $1.0\ \text{g cm}^{-3}$ to get 50 cm^3, instead of by the $0.2\ \text{g cm}^{-3}$ that each cubic centimetre of syrup actually adds when it displaces water. *(Wrong density used)*
- **H** (875 cm^3): Read the 1.05 kg as the mass of the syrup rather than of the finished drink, and converted it with the syrup's density: $\dfrac{1050}{1.2} = 875\ \text{cm}^3$. The carton holds 1050 g of drink altogether, of which only 300 g is syrup. *(Stated mass assigned to the syrup)*

Common mistake. Assuming a mixture always sits halfway between its ingredients and splitting the carton equally. Equal volumes would give $\dfrac{1200 + 1000}{2} = 1100\ \text{kg m}^{-3}$, not the $1050\ \text{kg m}^{-3}$ stated: the drink is only a quarter of the way up from water, so only a quarter of it is syrup.

Takeaway. The Cheat Code: when volumes add, the mixture's density lands between the two ingredient densities in exactly the proportion of the volumes. Measure how far along the gap from the lighter liquid to the denser one the mixture sits, and that fraction is the fraction of the volume the denser liquid occupies.

Time-saving tip. Speed Heuristic: switch to g cm^{-3} and read the position on a scale rather than solving an equation. The gap from 1.00 to 1.20 is 0.20, the drink sits 0.05 along it, and $\frac{0.05}{0.20} = \frac{1}{4}$ of 1000 cm^3 is 250 cm^3.

Question 4

P3.7 · Energy · ★★☆☆☆ · 25 s

An object of mass 5 kg is dropped from rest from a height of 45 m above the ground. Assuming negligible air resistance and $g = 10$ N kg^{-1}, what is its speed just before hitting the ground?

- **A.** 15 m s^{-1}
- **B.** 150 m s^{-1}
- **C.** 21 m s^{-1}
- **D.** 3 m s^{-1}
- **E.** 900 m s^{-1}
- **F.** 90 m s^{-1}
- **G.** 450 m s^{-1}
- **H.** 30 m s^{-1}

Answer H. Key idea

Assuming no energy is lost to heat/friction, the total mechanical energy is conserved. Initial Gravitational Potential Energy (mgh) converts perfectly into Kinetic Energy (1/2 mv^2) or Elastic Potential Energy.

Worked solution

1. Apply conservation of energy

Initial GPE = Final KE $mgh = \frac{1}{2}mv^2$

2. Cancel mass and solve for v

$$gh = \frac{1}{2}v^2 \implies v^2 = 2gh \implies v = \sqrt{2gh}$$

3. Substitute values

$$v = \sqrt{2 \times 10 \times 45} = \sqrt{900} = 30 \text{ m s}^{-1}$$

Matches Option **H**.

Why the other options are wrong

- **A** (15 m s^{-1}): Moved the half across the energy equation as a halving instead of a doubling: from $mgh = \frac{1}{2}mv^2$ wrote $v^2 = \frac{1}{2}gh = \frac{1}{2} \times 10 \times 45 = 225$, so $v = \sqrt{225} = 15$. The half multiplies v^2, so it crosses over as $v^2 = 2gh = 900$ and $v = 30$. The same value comes from quoting the average speed of the fall, $h \div t = 45 \div 3 = 15$, which is half the final speed for a body starting from rest. *(Factor of two on the wrong side)*
- **B** (150 m s^{-1}): Arises from a common inversion, algebraic sign error, or omitting an intermediate conversion factor. *(Calculation / Conceptual Error)*
- **C** (21 m s^{-1}): Arises from a common inversion, algebraic sign error, or omitting an intermediate conversion factor. *(Calculation / Conceptual Error)*

- **D** (3 m s^{-1}): Stopped one line early and reported the time of flight as though it were the speed: $45 = \frac{1}{2} \times 10 \times t^2$ gives $t^2 = 9$ and $t = 3$, which is the number of seconds the fall takes. The speed still has to be found from $v = gt = 10 \times 3 = 30$. *(Fall time quoted as the speed)*
- **E** (900 m s^{-1}): Arises from a common inversion, algebraic sign error, or omitting an intermediate conversion factor. *(Calculation / Conceptual Error)*
- **F** (90 m s^{-1}): Took the fall time from $h = \frac{1}{2}gt^2$ but never rooted it: wrote $t = 2h/g = 90 \div 10 = 9$ s instead of $t = \sqrt{2h/g} = \sqrt{9} = 3$ s, then $v = gt = 10 \times 9 = 90$. With the correct $t = 3$ s the speed is $10 \times 3 = 30$. *(Square root dropped when finding the fall time)*
- **G** (450 m s^{-1}): Arises from a common inversion, algebraic sign error, or omitting an intermediate conversion factor. *(Calculation / Conceptual Error)*

Common mistake. Multiplying by the mass or forgetting to square root 2gh.

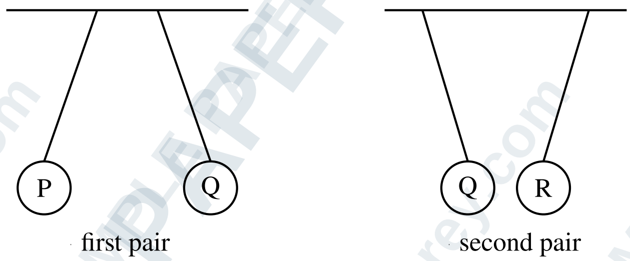
Takeaway. **The Cheat Code:** In GPE to KE conversions, the mass (m) always cancels out (mgh = 1/2 mv^2 -> v = sqrt(2gh)). If mass is given in the prompt, it's a distractor designed to waste your calculation time. Ignore it.

Time-saving tip. Speed Heuristic: Look at the relative magnitudes and units in the multiple-choice options to eliminate extreme or impossible values immediately.

Question 5

P1.1 · Electricity · ★★☆☆☆ · 85 s

Three light insulating spheres hang on nylon threads in a dry laboratory. Sphere Q was charged by stroking it with a silk cloth, and the cloth was afterwards found to be negatively charged. Spheres P and R had each been given a charge of their own beforehand. The spheres are then brought close in pairs, and they hang as shown. Assume no charge leaks away to the air or along the threads during the tests. Which statement about sphere R is correct?



A. R is positively charged, having lost electrons when it was charged.
B. R is negatively charged, having gained electrons when it was charged.
C. R is negatively charged, having lost electrons when it was charged.
D. R is positively charged, having gained electrons when it was charged.
E. R is uncharged, and is pulled towards Q only because Q is charged.

Answer B. Key idea

Rubbing two insulators together can move electrons and nothing else, so the material that ends up holding the extra electrons is the negative one and its partner is left positive. Once spheres carry charge, the way they hang shows their signs, because like charges repel and unlike charges attract.

Worked solution

1. Fix the sign of sphere Q

Charging by rubbing moves electrons only. The silk cloth finished negatively charged, so the silk gained electrons, and those electrons came off sphere Q. Sphere Q is therefore short of electrons and carries a positive charge.

2. Read the second pair, then count electrons

In the second pair the threads lean inwards, so Q and R are pulling towards each other: this is attraction. Both spheres carry a charge, and unlike charges attract, so R must carry the opposite sign to Q. Q is positive, so R is negative, and a negative sphere is one holding more electrons than protons. R gained electrons when it was charged.

Sanity check: the first pair hangs apart, which is repulsion, so P carries the same sign as Q, positive. That makes the three spheres positive, positive and negative, and exactly one of the two pairs tested holds unlike charges, which is the one drawn leaning together.

Matches Option **B**.

Why the other options are wrong

- **A** (R is positively charged, having lost electrons when it was charged.): Treats the inward lean of Q and R as evidence that their charges match, which makes R positive like Q, and then correctly pairs a positive charge with lost electrons. The lean is inwards, so that pair attracts and its charges are unlike. *(Interaction rule inverted)*
- **C** (R is negatively charged, having lost electrons when it was charged.): Gets the sign right, R negative, but books it as a loss of electrons. Losing electrons leaves a shortage of negative charge and so gives a positive sphere; a negative sphere is one that has gained electrons. *(Sign attached to the wrong electron move)*
- **D** (R is positively charged, having gained electrons when it was charged.): Makes both slips at once: takes the inward lean as repulsion, so R is called positive like Q, and then attaches that positive charge to a gain of electrons. Gaining electrons gives a negative sphere, so the two halves of the statement contradict each other. *(Interaction rule and electron count both inverted)*
- **E** (R is uncharged, and is pulled towards Q only because Q is charged.): Leans on the fact that a charged object can pull an uncharged one towards it, so the attraction is read as needing no charge on R. The stem states that R had already been given a charge of its own, so this is an attraction between two charged spheres and R cannot be neutral. *(Attraction assumed to show an uncharged sphere)*

Common mistake. Reading the inward lean of the second pair as a sign that Q and R match. Threads that lean together show attraction, and attraction between two charged spheres means opposite signs; it is the pair hanging apart, P and Q, that shares a sign.

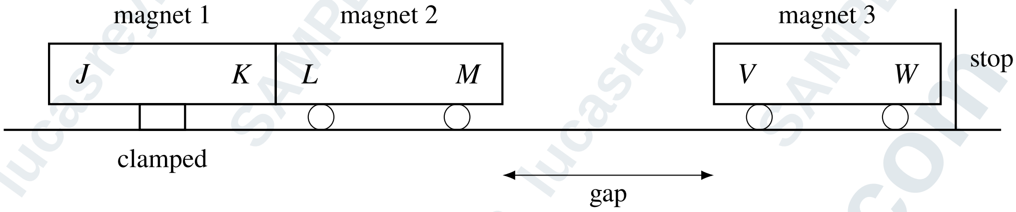
Takeaway. **The Cheat Code:** Only electrons move, so negative means extra electrons and positive means missing ones. Then let the threads speak: leaning together is unlike, hanging apart is like.

Time-saving tip. Speed Heuristic: settle the cloth first. Whatever the silk gained, Q lost, so Q is positive before you even look at the diagram, and the second pair then fixes R in a single move.

Question 6

P2.1 · Magnetism and electromagnetism · ★★☆☆☆ · 85 s

Three identical bar magnets sit on low-friction trolleys on a straight horizontal rail, as shown. The left-hand magnet is clamped, and the other two are free to slide. When they are released, magnets 1 and 2 close up until they touch, while magnet 3 runs away from magnet 2 and rests against an end stop. A compass test shows that end J is a north pole. Which two lettered ends are both north poles?



A. K and M
B. J and M
C. L and V
D. J and L
E. J and K

Answer D. Key idea

Every bar magnet carries a north pole at one end and a south pole at the other, so fixing one end of a magnet fixes its other end automatically. Between two magnets the rule runs one way only: unlike poles attract and like poles repel, so watching what a free magnet does identifies the pair of faces nearest to each other. Chaining those two facts along a row lets one known pole propagate through every magnet in the line, because each observed movement settles a junction and each magnet then settles its own far end.

Worked solution

1. Work along the row as far as magnet 2

End J is a north pole, and the two ends of a single bar magnet are always opposite poles, so K is a south pole.

Magnets 1 and 2 have pulled themselves into contact, and attraction happens only between unlike poles. The end of magnet 2 facing K is L, so L must be unlike K: L is a north pole. Its far end M is therefore a south pole.

2. Cross the open gap to magnet 3

Magnet 3 has been pushed away and is held against the stop, and repulsion happens only between like poles. The end of magnet 3 facing M is V, so V is like M, making V a south pole and the far end W a north pole.

Reading the row from left to right gives N S, then N S, then S N. The north poles are J, L and W, and the only listed pair drawn entirely from those three is J and L.

Sanity check: with that labelling the contact between magnets 1 and 2 is a south face meeting a north face, which does attract, and the open gap is a south face meeting a south face, which does repel. Both observations are reproduced, so the labelling is consistent. Turning magnet 3 end for end would let it close the gap, which is the standard demonstration of the same rule.

Matches Option **D**.

Why the other options are wrong

- **A** (K and M): Attached the compass result to the wrong end of magnet 1, taking K as north so that J is south. The contact then makes L south and M north, and the repulsion makes V north and W south, leaving K, M and V as the north poles and K and M as the listed pair. *(Known pole placed on the wrong end)*

- **B** (J and M): Swapped the two rules, taking attraction as evidence of like poles and repulsion as evidence of unlike poles. Then K is south, the contact makes L south and M north, and the repulsion makes V south and W north, so the north poles come out as J, M and W. *(Attraction and repulsion rules exchanged)*
- **C** (L and V): Applied the rule correctly at the contact but read the open gap as attraction as well, on the idea that magnet 3 had simply not finished moving. That makes V unlike M, so V is north, and the north poles are taken to be J, L and V. *(Gap read as attraction)*
- **E** (J and K): Treated each magnet as though both of its ends were the same pole, so J north forces K north as well. The contact then makes both L and M south and the repulsion makes both V and W south, leaving J and K as the only north poles. *(Both ends of one magnet taken alike)*

Common mistake. Assuming that the magnets which ended up touching must have like poles facing each other, on the loose idea that similar things attract. The rule runs the other way round, and here it decides everything: the faces in contact are unlike, while the faces on either side of the open gap are alike.

Takeaway. **The Cheat Code:** one known pole unlocks a whole row. Alternate N and S across each magnet's own length, put unlike poles at every contact and like poles across every gap that has opened, and the six labels fall out in a single sweep from left to right.

Time-saving tip. Speed Heuristic: write the six letters in a line and fill them in one pass, flipping the pole within each magnet, keeping unlike poles where the magnets touch and like poles across the gap. The chain is finished by the time you reach W, so the options only have to be scanned once.

Question 7

P2.3 · The motor effect · ★★☆☆☆ · 45 s

A wire of length 0.1 m carries a current of 3 A perpendicular to a magnetic field of flux density 1.2 T. Find the force on the wire.

A. 0.25 N
B. 4.30 N
C. 0.51 N
D. 0.36 N
E. 0.12 N
F. 3.60 N
G. 0.30 N
H. 36.00 N

Answer D. Key idea

The motor effect force on a current-carrying wire perpendicular to a field: $F = BIL = 1.2\times3\times0.1 = 0.36$ N
Direction from Fleming's LEFT-HAND rule (thumb = force, first finger = field, second finger = current).
If the

Worked solution

The motor effect force on a current-carrying wire perpendicular to a field:

$F = BIL = 1.2 \times 3 \times 0.1 = 0.36$ N

Direction from Fleming's LEFT-HAND rule (thumb = force, first finger = field, second finger = current).

If the wire runs PARALLEL to the field, F = 0, the formula needs the perpendicular arrangement (or sin θ).

Matches Option **D**.

Why the other options are wrong

- **A** (0.25 N): Rearranged the formula the wrong way and put the flux density underneath: $IL/B = (3 \times 0.1) \div 1.2 = 0.3 \div 1.2 = 0.25$ N. B is a factor in $F = BIL$, not a divisor, so the product is $0.3 \times 1.2 = 0.36$ N. *(Flux density divided instead of multiplied)*
- **B** (4.30 N): Added the quantities, the formula is a product. *(Conceptual Error)*
- **C** (0.51 N): Arithmetic slip. *(Arithmetic Error)*
- **E** (0.12 N): Left the current out of the product and multiplied only the flux density by the length: $BL = 1.2 \times 0.1 = 0.12$ N. $F = BIL$ needs all three, so the 3 A must multiply in as well: $0.12 \times 3 = 0.36$ N. *(Current omitted)*
- **F** (3.60 N): Forgot the length, F = BIL needs all three. *(Arithmetic Error)*
- **G** (0.30 N): Omitted the flux density. *(Arithmetic Error)*
- **H** (36.00 N): Divided by the length instead of multiplying by it: $BI/L = (1.2\times3)\div0.1 = 3.6\div0.1 = 36.00$ N. Dividing by 0.1 multiplies by ten, so this is one hundred times the true force; multiplying by 0.1 gives $3.6 \times 0.1 = 0.36$ N. *(Length inverted)*

Common mistake. Omitting a factor or adding the quantities.

Takeaway. **The Cheat Code:** F = BIL, 'BIL' rhymes with 'VIL'ence: force needs all three attackers. Left hand for motors, right hand for generators.

Time-saving tip. Write the ratio with the quantity you want on top. Set out that way, the substitution cannot go in upside down.

Question 8

P1.1 · Electricity · ★★☆☆☆ · 85 s

A polymer belt runs over a rubber drum, both insulators and both initially uncharged. Friction leaves the belt carrying −7.2 nC. With the electron charge 1.6×10^{-19} C, how many electrons has the drum lost?

A. 7.2×10^{10}
B. 4.5×10^{13}
C. 9.0×10^{10}
D. 4.5×10^{19}
E. 4.5×10^{10}
F. 2.2×10^{-11}
G. 2.25×10^{10}
H. 4.5×10^{28}

Answer E. Key idea

Rubbing two insulators together charges them by moving electrons, and electrons are the only thing that moves: the protons stay locked in the nuclei of both materials. Nothing is created either, so if the two bodies begin uncharged, every electron one of them gains is an electron the other has lost, and the two final charges are equal in size and opposite in sign. Charge itself comes in whole electrons, so a measured charge divided by the charge on one electron gives the number that changed hands.

Worked solution

1. Turn the belt's charge into the drum's charge

The belt ends up negative, so the belt has gained electrons. Friction cannot create charge and cannot move protons, so those electrons came from the only other body in contact, the drum. Both started uncharged, which means the drum is left short of exactly the electrons the belt has taken:

$$Q_{\text{drum}} = +7.2 \text{ nC} = +7.2 \times 10^{-9} \text{ C}.$$

The number lost by the drum is therefore the same number the belt gained, not half of it and not twice it.

2. Divide by the charge on one electron

$$n = \frac{Q}{e} = \frac{7.2 \times 10^{-9}}{1.6 \times 10^{-19}}.$$

Split the division: $7.2 \div 1.6 = 4.5$, and $10^{-9} \div 10^{-19} = 10^{10}$, so

$$n = 4.5 \times 10^{10}.$$

Sanity check by multiplying back: $4.5 \times 10^{10} \times 1.6 \times 10^{-19} = 7.2 \times 10^{-9}$ C, the charge stated. A second check on the size: a few tens of thousands of millions of electrons sounds enormous, but a gram of matter holds of order 10^{23} electrons, so the drum has parted with a vanishing fraction of what it holds, which is why the belt and drum look completely unchanged.

Matches Option **E**.

Why the other options are wrong

- **A** (7.2×10^{10}): Divided by the power of ten alone and never divided by the 1.6: $7.2\times10^{-9} \div 10^{-19} = 7.2\times10^{10}$. The digits divide too, and $7.2 \div 1.6 = 4.5$, so the count is 4.5×10^{10}. *(Electron charge digits dropped)*
- **B** (4.5×10^{13}): Converted the prefix as though nano meant 10^{-6}: $Q = 7.2 \times 10^{-6}$ C, so $n = 7.2 \times 10^{-6} \div 1.6 \times 10^{-19} = 4.5 \times 10^{13}$. Nano is 10^{-9}, a thousand times smaller than micro, which pulls the count back to 4.5×10^{10}. *(Micro used for nano)*
- **C** (9.0×10^{10}): Counts the transfer twice, adding the electrons the belt gained to the electrons the drum lost: $2 \times 4.5 \times 10^{10} = 9.0 \times 10^{10}$. They are the same electrons. *(Double counting)*
- **D** (4.5×10^{19}): Drops the nano prefix and divides 7.2 C by the electron charge: $7.2 \div 1.6 \times 10^{19} = 4.5 \times 10^{19}$. One nanocoulomb is 10^{-9} C. *(Prefix ignored)*
- **F** (2.2×10^{-11}): Inverts the division, working out $1.6\times10^{-19} \div 7.2\times10^{-9} = 2.2\times10^{-11}$. A count of electrons cannot be a fraction of one. *(Inverted ratio)*
- **G** (2.25×10^{10}): Halves the charge first, on the idea that the 7.2 nC is shared between the belt and the drum: $3.6 \times 10^{-9} \div 1.6 \times 10^{-19} = 2.25 \times 10^{10}$. The two bodies each carry the full 7.2 nC, opposite in sign. *(Charge shared)*
- **H** (4.5×10^{28}): Wrote the nano prefix with a positive exponent, taking $Q = 7.2\times10^{9}$ C: $7.2\times10^{9} \div 1.6\times10^{-19} = 4.5 \times 10^{28}$. A nanocoulomb is a billionth of a coulomb, so the exponent is -9 and $(-9) - (-19) = +10$. *(Prefix exponent sign)*

Common mistake. Assuming that a negative body and a positive body must have taken part in two separate exchanges, so that the electron count has to be shared out or doubled. One single transfer produced both charges at once, so the number the drum lost is exactly the number the belt gained.

Takeaway. The Cheat Code: Charging by friction is bookkeeping with one entry. Electrons move one way, so the negative body gained them, the positive body lost the same number, and the count is always the measured charge divided by 1.6×10^{-19} C.

Time-saving tip. Speed Heuristic: Do the digits and the powers of ten separately. $7.2 \div 1.6 = 4.5$ takes a moment, and -9 minus -19 gives $+10$, so the answer is 4.5×10^{10} before you have written the fraction out.

Question 9

P4.4 · Thermal physics · ★★★☆☆ · 90 s

A camping stove's electric plate draws 1200 W from a generator, and 360 W of this is lost to the pan and the surroundings. The pan holds 2.0 litres of water at 20 °C. Water has density 1000 kg m^{-3} and specific heat capacity 4200 J kg^{-1} K^{-1}. Assume the plate reaches its steady output immediately and the loss stays constant. How long does the water take to reach 80 °C?

- **A.** 600 s
- **B.** 1000 s
- **C.** 200 s
- **D.** 800 s
- **E.** 1050 s
- **F.** 294 s
- **G.** 1400 s
- **H.** 420 s

Answer A. Key idea

The energy a body of water must absorb is fixed by its mass, its specific heat capacity and its temperature rise, through $E = mc\Delta T$, and nothing about the heater changes that figure. The heater decides only how fast the energy is handed over. So the calculation splits cleanly in two: find the energy from the water alone, then find the rate at which energy actually arrives in the water, which is the supplied power minus whatever is lost, and divide the first by the second.

Worked solution

1. Mass of water in the pan

2.0 litres is 2.0×10^{-3} m^3, so

$m = \rho V = 1000 \times 2.0 \times 10^{-3} = 2.0$ kg.

2. Energy the water must absorb

The temperature rise is $\Delta T = 80 - 20 = 60$ K, and a rise of one kelvin is the same size as a rise of one degree Celsius, so

$E = mc\Delta T = 2.0 \times 4200 \times 60 = 504000$ J = 504 kJ.

3. Power that actually reaches the water

Of the 1200 W drawn from the generator, 360 W never gets into the water, so

$P_{\text{useful}} = 1200 - 360 = 840$ W.

4. Time to deliver that energy

$$t = \frac{E}{P_{\text{useful}}} = \frac{504000}{840} = 600 \text{ s}.$$

Sanity check: $840 \times 600 = 504000$ J, exactly the energy required. Ten minutes to take two litres from 20 °C to 80 °C on a plate of roughly one kilowatt is the sort of time a camping stove really needs.

Matches Option **A**.

Why the other options are wrong

- **B** (1000 s): Added the two temperatures rather than subtracting them, using $\Delta T = 80 + 20 = 100$ K: $E = 2.0 \times 4200 \times 100 = 840000$ J, then $840000 \div 840 = 1000$ s. The water only has to climb the 60 K between the two readings. *(Temperatures added)*
- **C** (200 s): Took the 20 °C the water starts at as the temperature change: $E = 2.0 \times 4200 \times 20 = 168000$ J, then $168000 \div 840 = 200$ s. ΔT is the difference between the two readings, $80 - 20 = 60$ K. *(Starting temperature used as ΔT)*
- **D** (800 s): Used the final temperature as the rise instead of the change: $E = 2.0 \times 4200 \times 80 = 672000$ J, then $672000 \div 840 = 800$ s. *(Final temperature used as ΔT)*
- **E** (1050 s): Subtracted the loss twice, once from the plate's supply and again from the power reaching the water: $1200 - 360 - 360 = 480$ W, giving $504000 \div 480 = 1050$ s. *(Loss double counted)*
- **F** (294 s): Noticed that 360 W of 1200 W is 30%, then took 30% off the time found from the full power instead of dividing by the 70% that arrives: $504000 \div 1200 = 420$ s, then $420 \times 0.70 = 294$ s. Losing power makes the heating slower, so the time is $420 \div 0.70 = 600$ s. *(Efficiency multiplied instead of divided)*
- **G** (1400 s): Divided by the wasted power rather than the delivered power, $504000 \div 360 = 1400$ s, which is the time the losses alone would take to carry away that much energy. *(Wrong power used)*
- **H** (420 s): Divided by the full power drawn from the generator, $504000 \div 1200 = 420$ s, treating every watt as reaching the water and ignoring the stated 360 W loss. *(Loss ignored)*

Common mistake. Dividing by the 1200 W the plate draws rather than the 840 W that reaches the water. The wasted 360 W is 30% of the supply, so this makes the heating look 180 s quicker than it really is.

Takeaway. **The Cheat Code:** energy first, power second. Work out $mc\Delta T$ for the water on its own, then decide separately how many watts are actually delivering it, and divide only at the very end. Losses never change the energy the water needs, only the time taken to hand it over.

Time-saving tip. Speed Heuristic: cancel before multiplying and 504000 never has to be written. $4200 \times 60 = 252000$, and $252000 \div 840 = 300$, so the time is $2 \times 300 = 600$ s. Spotting that 840 is 2×420 and 420 divides 4200 ten times makes the whole thing mental.

Question 10

P4.2 · Thermal physics · ★★★☆☆ · 90 s

A paraffin lamp burns inside a tall glass chimney that is open at the top and pierced by a ring of small holes around its base; these openings are the only ways in or out. The lamp stands in a draught-free room whose air stays at a steady 20°C, while the flame keeps the air inside the chimney much hotter. Which statement correctly describes how air moves through the chimney, and why?

A. Air enters at the top and leaves through the base holes, because the cooler, denser room air sinks into the chimney and pushes the warm air out below it.

B. Air enters at the top and leaves through the base holes, because warming the air raises its density, so the hot air sinks and spills out through the holes.

C. No air passes through either opening, because the difference in density between the hot and the cool air holds the two bodies of air apart.

D. Air enters through the base holes and leaves at the top, because warming the air lowers its density, so the denser room air displaces it upwards.

E. Air enters through the base holes and leaves at the top, because hot gas always rises, whatever the density of the air surrounding it.

Answer D. Key idea

Heating a fluid makes it expand, so the same mass fills a larger volume and its density falls. Flow then follows from a comparison rather than from the temperature on its own: a less dense body of fluid is

> displaced upwards by the denser fluid around it, and whatever leaves at one opening has to be replaced through another, which is what turns a single rising column into a continuous circulation.

Worked solution

1. What the flame does to the density of the air

The flame warms the air inside the chimney. A warmed gas expands, so the same mass of air now occupies a larger volume, and density is mass divided by volume. The air in the chimney is therefore less dense than the 20°C air filling the room.

2. What a difference in density does

A body of fluid that is less dense than the fluid surrounding it does not stay where it is. The denser fluid, heavier for the same volume, settles underneath it and displaces it upwards. Here the room air is the denser of the two, so it pushes the warm column of chimney air up and out through the open top. The rising is not something the hot gas does of its own accord: it is what the surrounding air does to it.

3. Close the loop

Air that leaves the top has to be replaced, and the ring of holes at the base is the only other opening, so room air is drawn in there. The result is a steady upward draught: in at the bottom, up past the flame, out at the top, lasting as long as the temperature difference does.

Sanity check: cover the base holes and the replacement air cannot get in, so the draught stops. That is exactly why lamps of this design carry their openings at the bottom rather than at the top.

Matches Option **D**.

Why the other options are wrong

- **A** (Air enters at the top and leaves through the base holes, because the cooler, denser room air sinks into the chimney and pushes the warm air out below it.): Gets the density comparison right and the geometry wrong. The room air is indeed the denser of the two, but denser air entering at the top would have to drive the less dense warm air downwards past the flame and out at the base, which is the wrong way round for the lighter fluid. The cool air does move in, at the bottom. *(Conceptual, flow direction reversed)*
- **B** (Air enters at the top and leaves through the base holes, because warming the air raises its density, so the hot air sinks and spills out through the holes.): Inverts the effect of temperature on density. Warming a gas expands it, so the same mass fills a larger volume and the density falls rather than rises. Sinking and an outflow at the base then follow logically from a false first step. *(Conceptual, temperature and density inverted)*
- **C** (No air passes through either opening, because the difference in density between the hot and the cool air holds the two bodies of air apart.): Treats a density difference as a barrier instead of as the cause of the flow. Two bodies of air of different density in contact do not sit still: the denser one settles beneath the lighter one, and that movement is exactly the convection current the chimney relies on. *(Conceptual, density difference read as static)*
- **E** (Air enters through the base holes and leaves at the top, because hot gas always rises, whatever the density of the air surrounding it.): Gets the direction of the draught right for a reason that does not hold. Hot gas does not rise of its own accord, it rises when the fluid around it is denser. Surround the same hot gas with air that is hotter still, at the same pressure, and it would sink, so the comparison of densities, not the temperature by itself, is what drives the flow. *(Conceptual, right direction from the wrong mechanism)*

Common mistake. Treating "hot air rises" as a property that hot air carries around with it. Rising is a comparison: the air goes up only because the air around it is denser at that moment. Put the same warm air into surroundings that are hotter still, at the same pressure, and it would sink instead.

Takeaway. **The Cheat Code:** In any convection question, name the two bodies of fluid and ask which is denser right now. The denser one moves in underneath, the less dense one is pushed up, and the opening the fluid leaves by fixes the opening it must enter by.

Time-saving tip. Speed Heuristic: split the options by flow direction before reading any of the reasons. The hot, expanded air is the least dense thing in the chimney, so it has to leave at the top, which kills the two options that push air out at the base and the one that says nothing moves. Of the two survivors, keep the reason that names a density difference rather than a rule about hot gas.

END OF SOLUTIONS

Questions 11 to 27 are in the full paper

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