2022 AUSTRALIAN SCIENCE OLYMPIAD EXAM

PHYSICS

TO BE COMPLETED BY THE STUDENT. USE CAPITAL LETTERS.

First Name: ………………..…..………… Last Name………………………………….

Date of Birth: ……/…..../..….

□ Male □ Female □ Unspecified Year 10 □ Year 11 □ Other: …….

Name of School: ……………………………………….………………..State: ……...

Examiners Use Only:

2022 AUSTRALIAN SCIENCE OLYMPIAD EXAM

PHYSICS

Time Allowed

Reading Time: 10 minutes
Examination Time: 120 minutes

INSTRUCTIONS

- *Attempt all questions in ALL sections of this paper.*
- Permitted materials: non-programmable, non-graphical calculator, pens, pencils, erasers and a ruler.
- Marks will not be deducted for incorrect answers.
- Ensure that diagrams are clear and labelled
- All numerical answers must have correct units

MARKS

Section A: 10 multiple choice questions	10 marks
Section B: Skateboarding	23 marks
Section C: Satellite	15 marks
Section D: Lasers and Atoms	13 marks
Section E: Unusual Physics	12 marks
TOTAL	**73 marks**

Integrity of Competition

If there is evidence of collusion or other academic dishonesty, students will be disqualified. Markers' decisions are final.

Section A: Multiple choice questions

Suggested Time: 20 minutes

For the following multiple choice questions, assume the acceleration due to gravity $g=10m/s^2$. Each question is worth one mark.

1. A pigeon of mass 0.5kg is happily seated atop the shell of a turtle of mass 5kg. What is the weight of the pigeon?

    a. 0.5kg
    b. 5 N
    c. 55 N
    d. 0 kg
    E. 5.5 kg

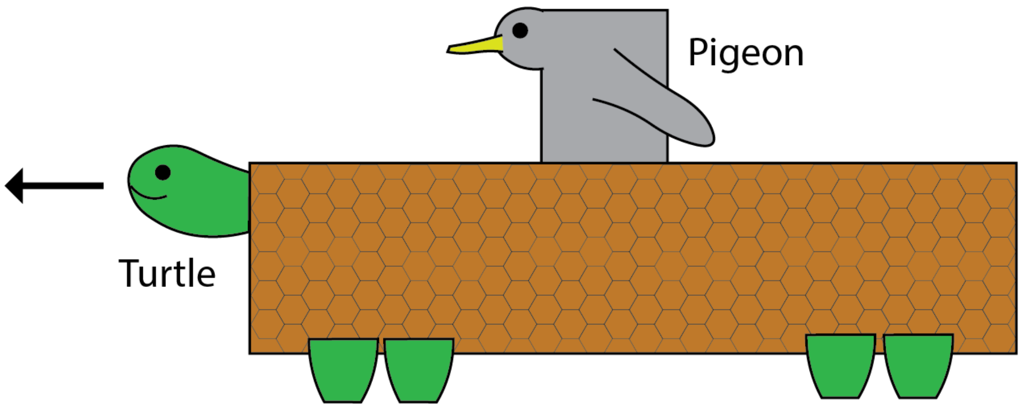
2. What is the force of the pigeon on the turtle?

    a. 0.5 kg
    b. 5 N
    c. 55 N
    d. 0 N
    e. 5.5 kg

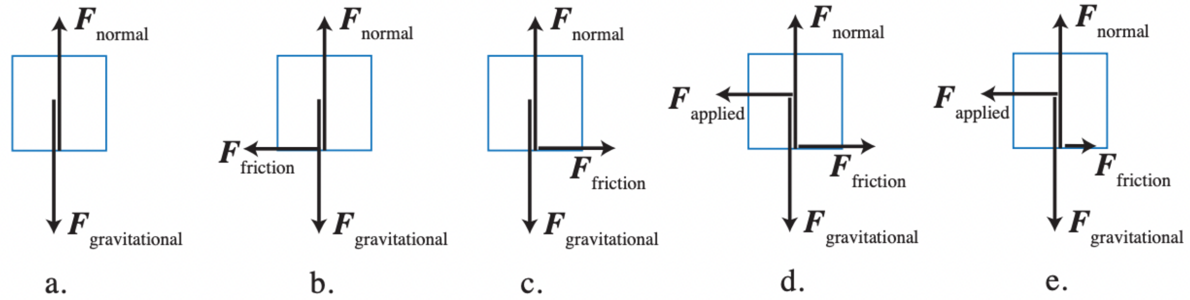
3. What is the force of the turtle on the pigeon?

    a. 0 N
    b. 50 N
    c. 55 N
    d. 5 N
    e. 0.5kg

4. Which of the following force diagrams best describes the forces on the pigeon when the turtle starts to walk to the left, as shown.



Assume the turtle moves only in the horizontal direction, and that its shell can be considered as a horizontal flat surface.



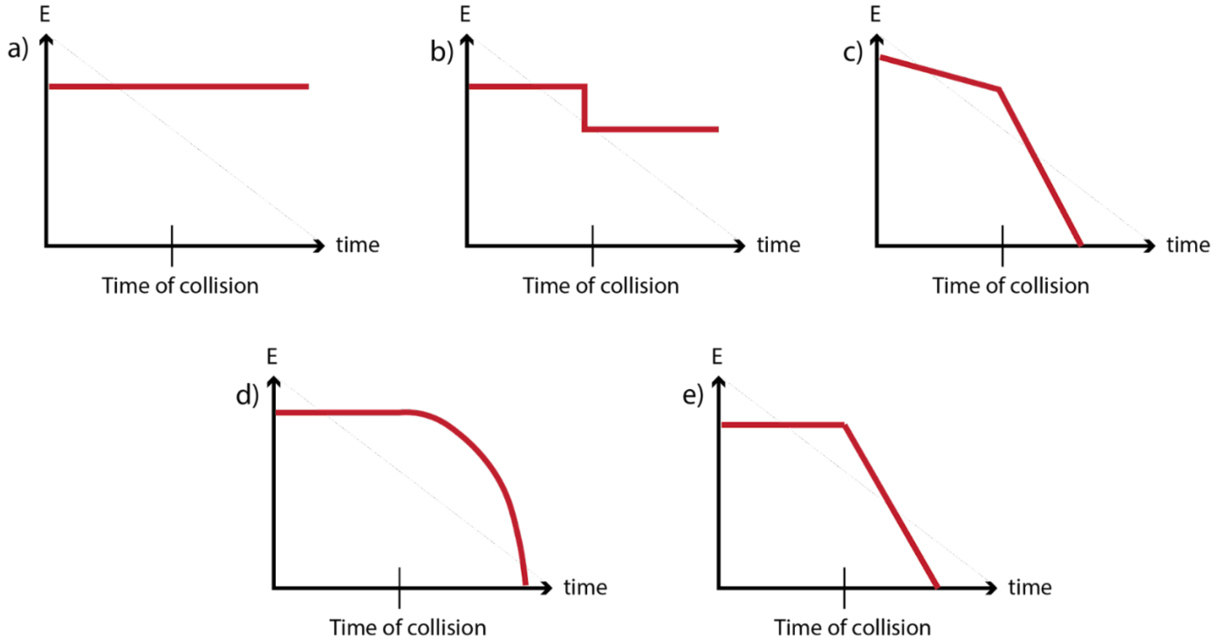
5. The pigeon sees its friend, an eagle, in the sky, and flies to meet the eagle who is gliding in the opposite direction. The eagle has a mass of 2kg. If the pigeon and eagle have the same kinetic energy, which of the following statements are correct.

a. The pigeon is moving at a speed two times that of the eagle.
b. The pigeon is moving at a speed four times that of the eagle.
c. The pigeon is moving at a speed half that of the eagle.
d. The pigeon is moving at a speed one quarter that of the eagle.
e. The pigeon and eagle are moving at the same speed.

6. Unfortunately, in their excitement to see each other, the pigeon and eagle collide mid-air while flying horizontally, directly at each other. Their wings get tangled up and so they are unable to fly. In the instant after their collision, which direction do the tangled-up birds go?

a. In the direction the pigeon was flying
b. In the direction the eagle was flying
c. The birds stop dead in the air
d. The birds fall straight downwards
e. More information is needed to answer this question

7. Which of the following graphs best describes the total mechanical energy of both the birds as a function of time for the birds before and after collision.



8. Alice wishes to measure the acceleration due to gravity for a falling object. However, unfortunately the only object she has on hand to drop is a tissue box. She wants to minimise the effect of air resistance, which creates a force in the opposite direction to an object's motion and therefore slows down the falling object. She films the object so error due to reaction time is negligible. Which of the following experimental set-ups is optimal?

a) Drop an empty tissue box from a low height, around 1 metre, and time how long it takes to fall.
b) Drop an empty tissue box from a higher height, around 10 metres, and time how long it takes to fall.
c) Drop a full tissue box from a low height, around 1 metre, and time how long it takes to fall.
d) Drop a full tissue box from a higher height, around 10 metres, and time how long it takes to fall.
e) All the above methods will give the same result

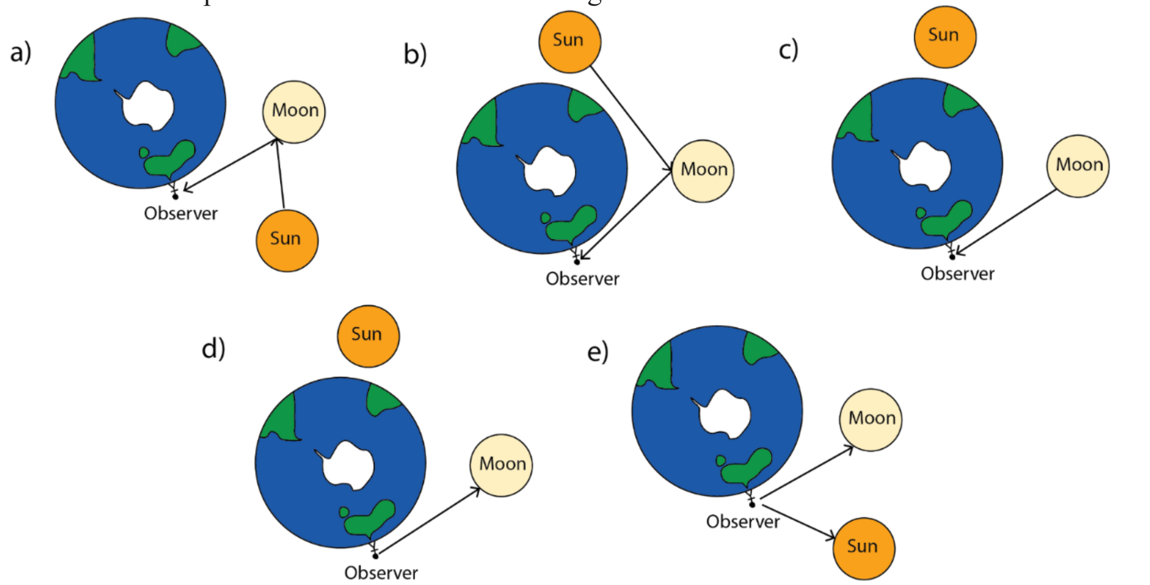
9. Newton's Law of Gravitation, the force due to gravity of an object with mass M on a different object of mass m, is given as:

$$F = \frac{GMm}{r^2}$$

Where G is the gravitational constant, 6.6743×10^{-11} m^3 kg^{-1} s^{-2}
Assuming G, M and m are constant, what combination of variables will give a straight-line relationship?

a. F vs r^2
b. F vs r
c. F vs 1/r
d. F vs $1/r^2$
e. None of the above

10. The moon can be visible in the sky at night even though it does not produce any light itself. Instead, the sun produces light, and the moon reflects this light. We use light diagrams to show the path of light rays as arrows, from when they are produced as a source (tail of arrow, –) to when they are observed (head of arrow, >). Which of the following light diagrams describe how an observer at the equator of the Earth can see the moon at night? Assume the Earth has no tilt, and the Earth and moon rotate in a flat plane around the sun. Note the figure is not to scale.



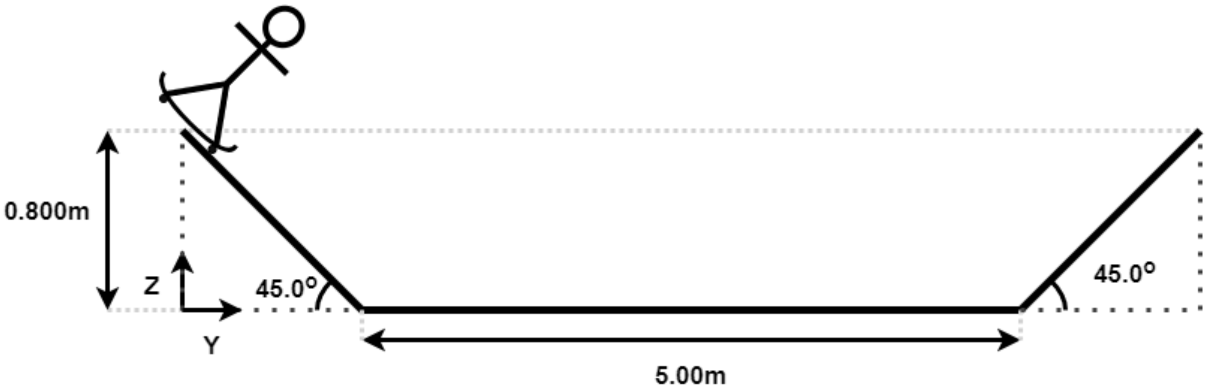
Section B: Skateboarding

Suggested time: 35 minutes

A skateboarder is testing out a new feature at their local skate park. It consists of two smooth ramps and a smooth flat surface between them as shown in the diagram below. The skater begins at the top of one ramp and lets the skateboard freely roll through the course. That is, they do not push off the ground or provide any 'boost' to the skateboard at any point.

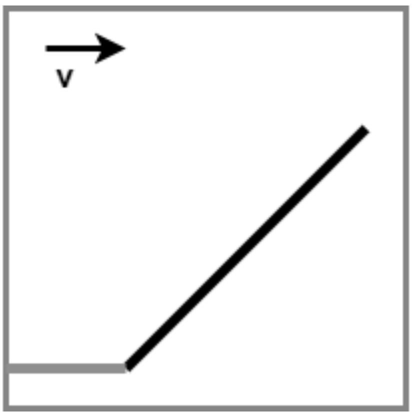
Assume throughout that the skater can smoothly transition from the ramp to the flat surface (without loss of energy). Take the acceleration due to gravity as $9.81 m/s^2$.

For all plotting questions, no calculations are required, only the general shape of the graph is expected.

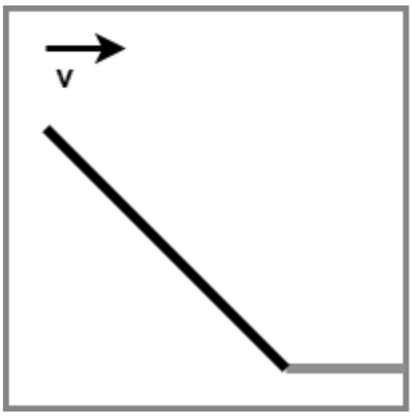


a. Draw a free-body-diagram of the skater on the ramp,

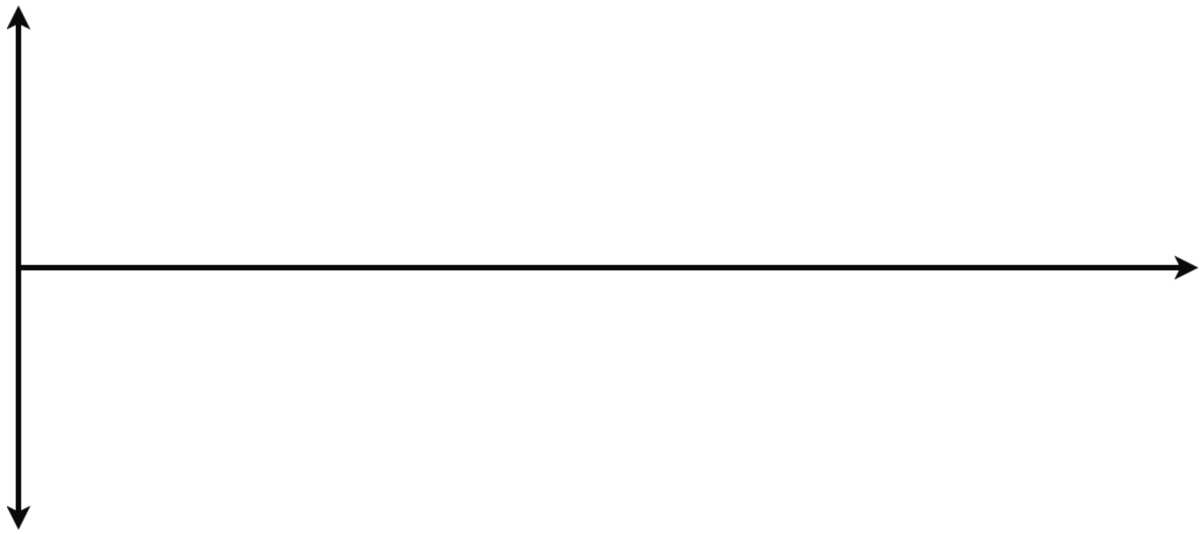
i) while going up the ramp: (1 mark)



ii) and going down the ramp: (1 mark)



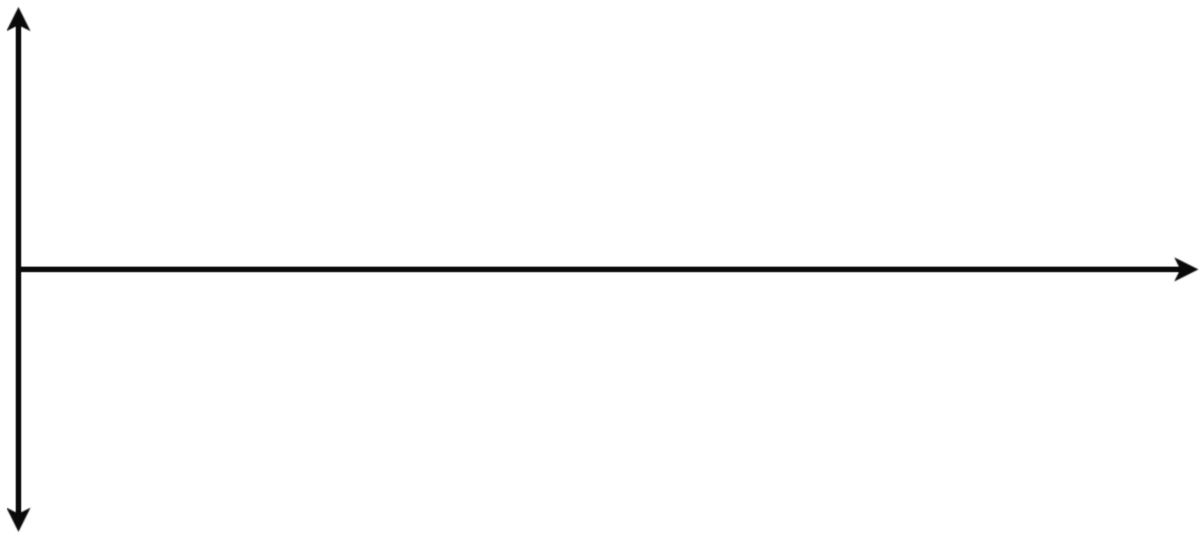
b. Sketch a plot of speed as a function of time of the skater for three laps. One lap involves the skater going down one ramp, across the flat and up the opposite ramp. (1 mark)



c. Now, on a single set of axes, sketch three different plots:

i. the skater's kinetic energy
ii. gravitational potential energy
iii. total mechanical energy

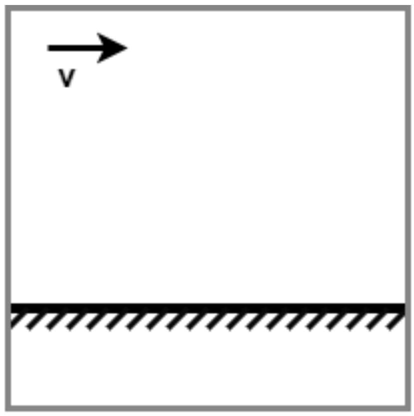
each as a function of time for three laps. (2 marks)



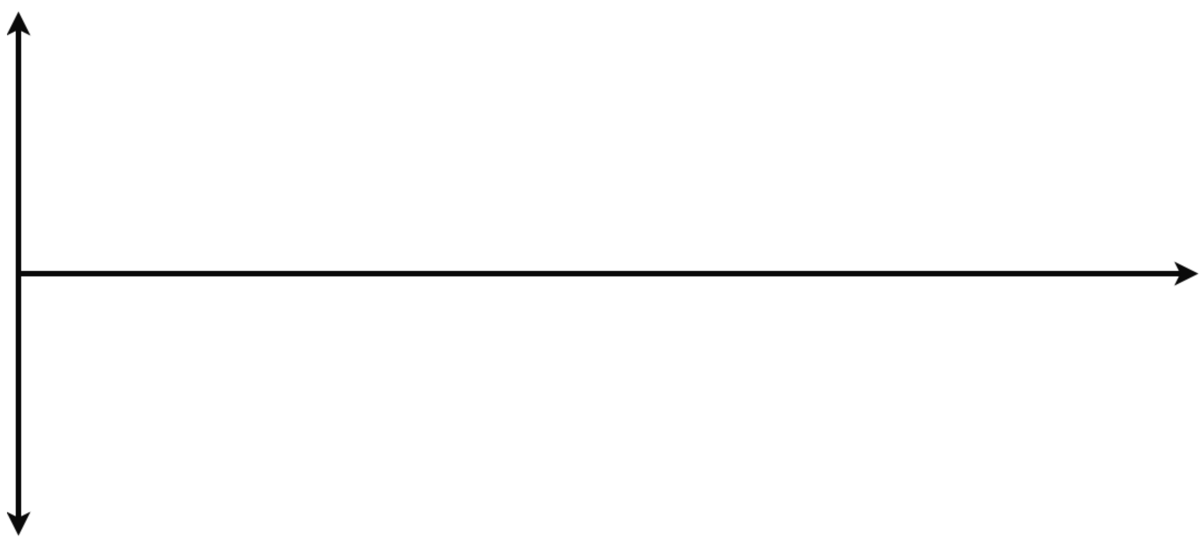
Part 2

Upon feedback from the skater, the council adds a rough material with some, but low friction to the flat surface. The ramps remain smooth and no dimensions are changed.

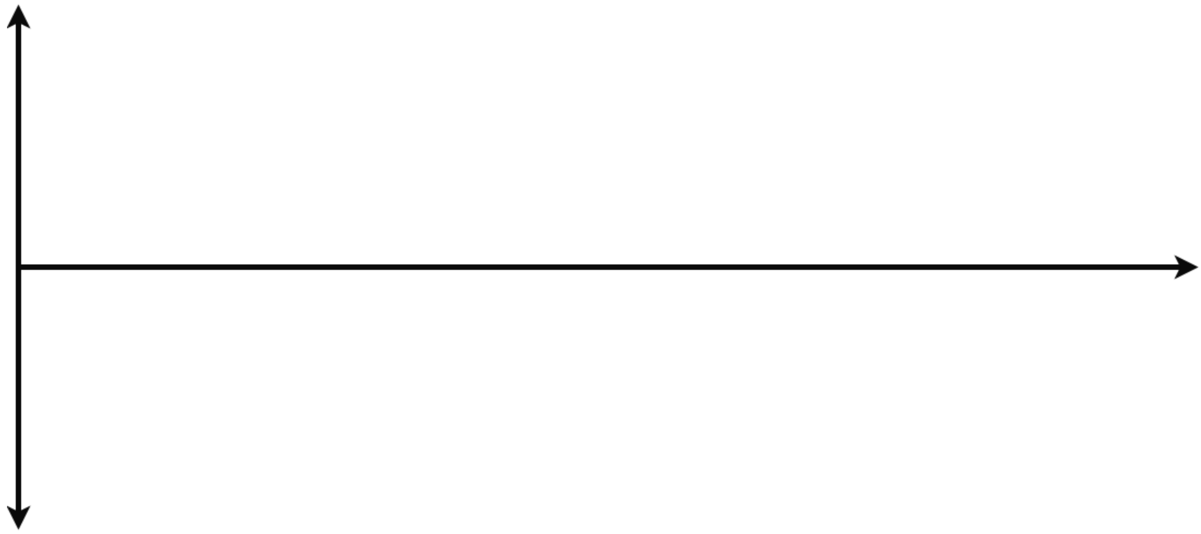
a. Draw a free body diagram of the skater on the new flat surface. (1 mark)



b. Sketch a plot of speed as a function of time of the skater for three laps, using the same definition of a lap as part one. Assume for this part that the skater does not stop during these laps. (2 marks)



c. Sketch a plot of **only** total mechanical energy as a function of time over three laps. (2 marks)



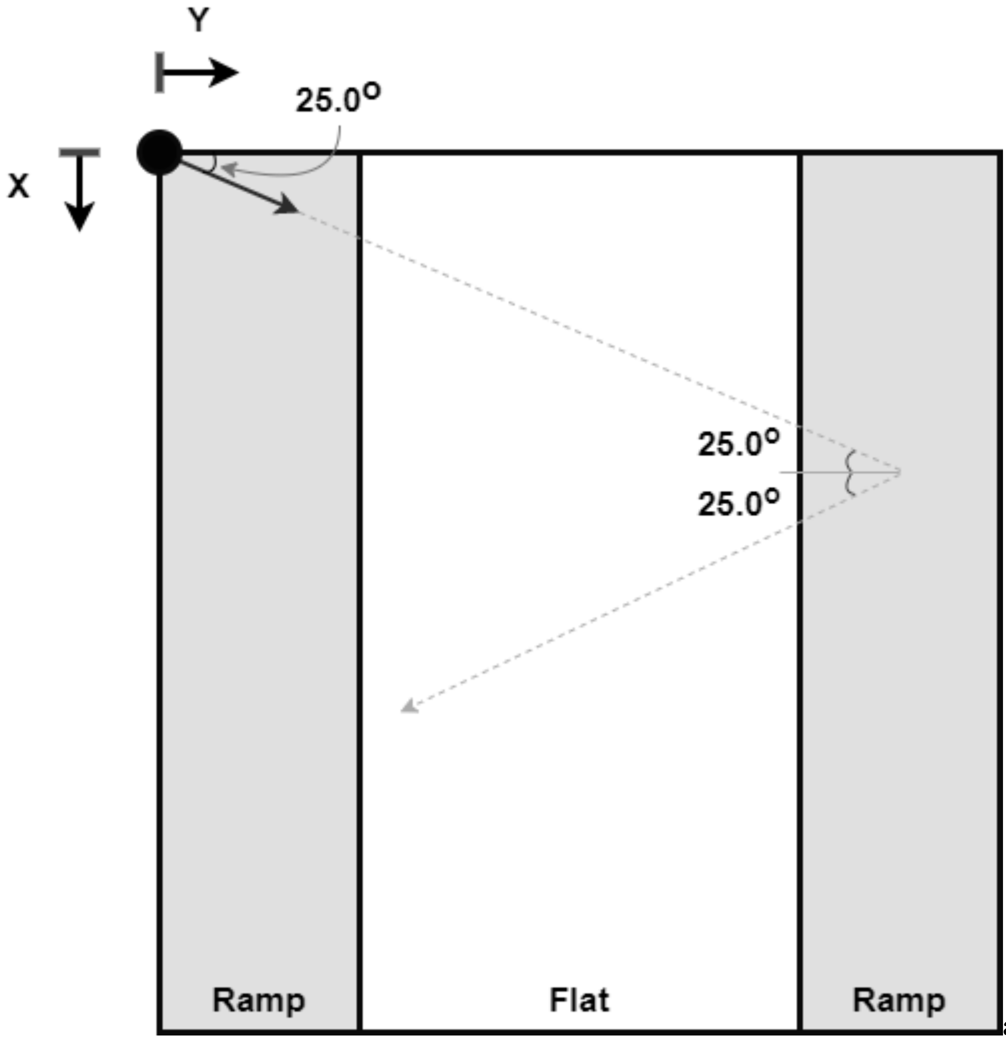
The friction coefficient, μ, of the rough material is 0.0150. Assume the skater and skateboard weigh 70.0kg.

d. How many full laps does the skater complete before they come to a stop? (3 marks)

e. What is the horizontal distance (in the y direction) of the skater from the top of the left ramp (origin indicated on the diagram) when they come to a stop? (2 marks)

Part 3

The skater now initially travels down the ramp at an angle, shown in the diagram below from a birds-eye view. Assume that at the end of each lap, the skater turns around and leaves the ramp



at the same angle they arrive at, reflected over the y-axis. The ramp has the same dimensions as in the first two parts. The rough material remains on the flat surface and the ramps remain smooth.

a. How many full laps does the skater complete before they come to a stop? (4 marks)

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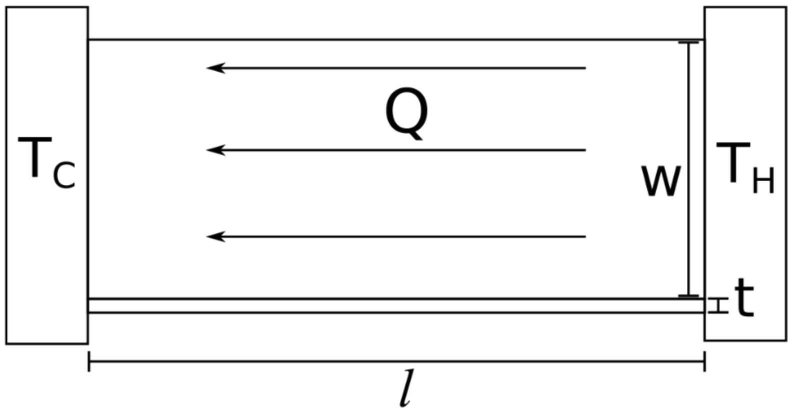
b. How far do they travel in the x-direction before they stop? (4 marks)

Section C: Satellite

Suggested time: 32 minutes

Heat flows primarily through convection, conduction, and radiation. Convection is the most dominant driver of heat flows on earth. In space however there is infamously no air, this causes a challenge for spacecraft design, as without careful consideration of conduction and radiation, the spacecraft may easily overheat or become too cold. Here we will investigate conductive heat flows such as when a heat sink is needed to be thermally coupled to a heat source in a spacecraft.

Consider a rectangular plate of metal of length l, width w, and thickness t. The heat which flows across the length of the plate via conduction is proportional to its width, thickness, and temperature difference across the length of the plate $\Delta T = T_H - T_C$, and is inversely proportional to the length of the plate.



The expression for the amount of heat flow across Q across the plate is:

$$Q = \frac{kwt\Delta T}{l}$$

This constant of proportionality, k, known as the thermal conductivity, it is material dependent. Heat can transfer more easily via conduction through materials with a high thermal conductivity.

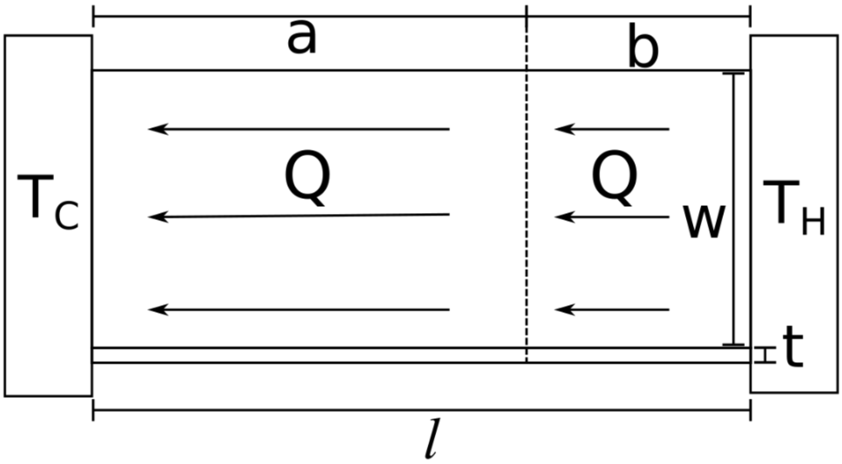
Consider a plate of width w, thickness t, length l, thermal conductivity k, and with a temperature difference T_C at its left side and T_H at its right side.

1. Using the values k = 160 W/(m.K), w = 5 cm, t = 3 mm, l = 20 cm, T_C = 270 K, T_H = 300 K, calculate the heat which flows through the plate. (1 mark)

Now we will explore the temperature of the plate at different points along its length. At either end the plate is connected to two heat reservoirs at T_C and T_H these are assumed to be so large that their temperature is constant.

Consider dividing this plate across its width into two plates of length a and b, with $a + b = l$.

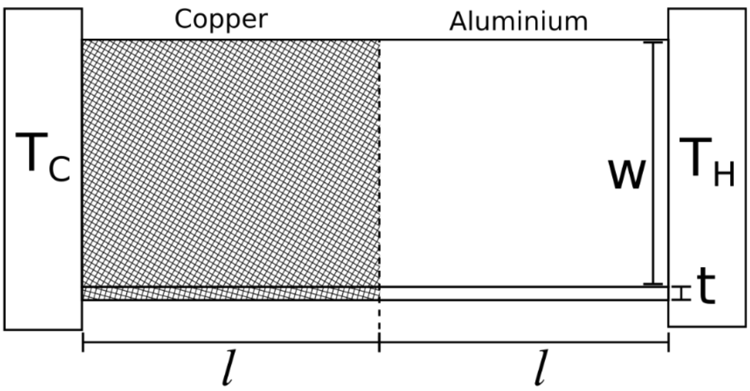
We will be considering steady state where the temperature of the plate does not change and so the heat which flows through both plates is the same. We can use this construction to find the temperature at any point along the plate by choosing different values of a.



2. What is the temperature ⅔ along the length of the plate from the left side? (1 mark)

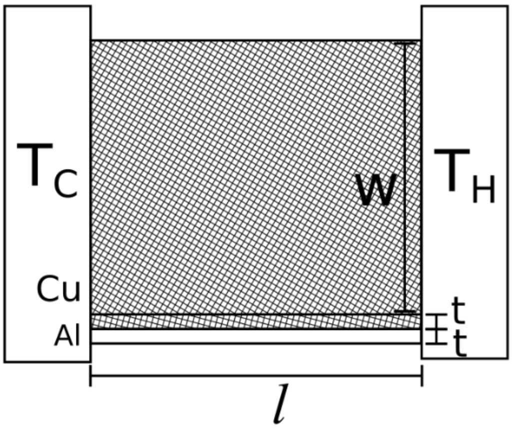
3. Draw a graph of the temperature of the rod as a function of distance from the left side. (3 marks)

Now imagine a copper plate joined along its width to an aluminium plate as shown in the diagram. The thermal conductivity of copper is about 2.5 times that of aluminium, both the copper and the aluminium plates have the same length l.



4. Is the temperature drop greater across the aluminium or copper plate? Justify your answer. (2 marks)

Imagine that the plates were not joined end to end but rather stacked on top of each other as shown in the diagram below.

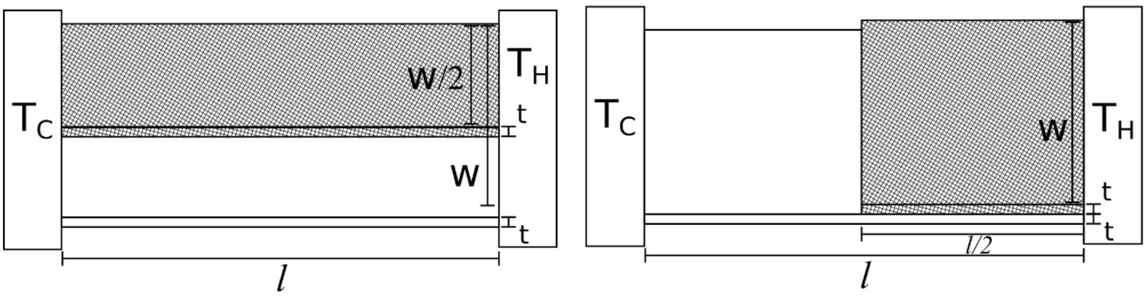


5. Calculate the maximum heat per second able to be conducted by the system if the temperature difference is to remain less than 3 K. (2 marks)

When trying to move heat from one part of a spacecraft to another, it is beneficial to design a conductive system which can transport a large amount of heat with a small temperature drop, while being as light as possible.

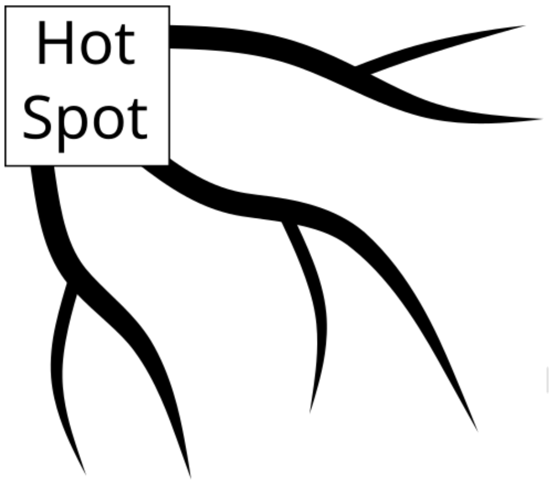
Alice and Bob are two engineers who have each designed a composite part which they believe to be better performing. They both have a base aluminium plate, however Alice has covered the top half of the plate with copper whereas Bob has covered the right half.

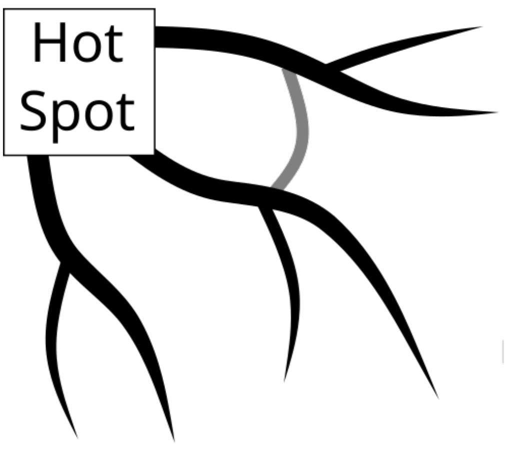
Alice claims that it is better to have the back half covered with copper as it provides a high conductivity path all the way from the hot end to the cold end.
Bob claims that his design is better as he gives the entire hot end a high conductivity path for as long as possible.

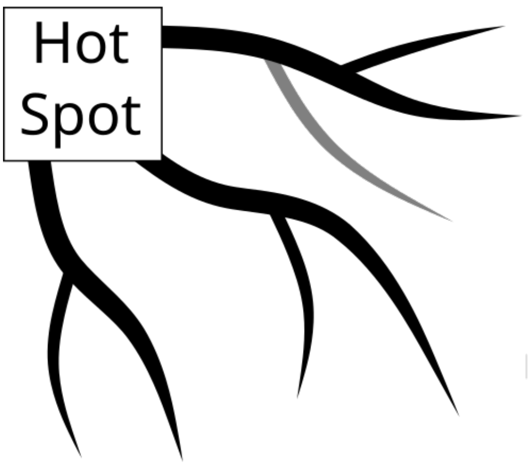


6. Whose reasoning is correct? Use equations to justify your answer. (2 marks)

A component of Alice and Bob's design is a hot spot and they need to cool it down. After some reading they find that a tree-like structure will work best to distribute the heat from the hot spot. They find however that they still need to squeeze out a bit more performance. As a modification to improve heat distribution Alice thinks that they should add extra aluminium connecting the branches together, however Bob thinks that it would be better to add in new branches.





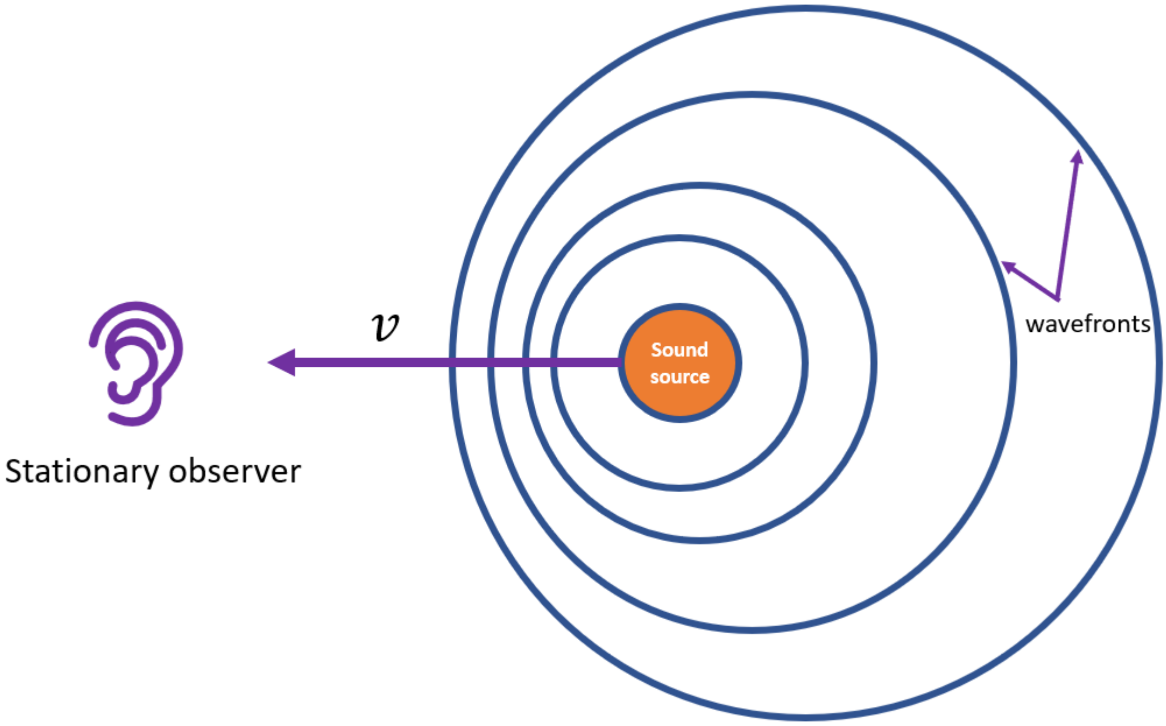


7. Whose modification will perform better? Be sure to justify your answer. (4 marks)

Section D: Lasers and Atoms

Suggested time: 15 minutes

1. If a sound source is moving with respect to an observer, a phenomenon known as the Doppler effect will be observed. This effect describes the change in frequency of a wave when there is relative motion between the wave source and the observer. For the case of a moving sound source, this effect can be explained by considering the wavefronts emitted by the source. In the direction the source is moving, the wavefronts will be 'bunched' together as shown below, contributing to a smaller wavelength observed. In the opposite direction, the wavefronts are spaced further apart, and a longer wavelength is seen.



This effect is apparent when a car approaches - as it moves towards you, the pitch you hear increases. As the car moves away, it is lowered in accordance with the Doppler effect. We can describe this frequency shift by:

$$f = \frac{c}{c \pm v_s} f_0$$

Where c is the speed of sound in the medium (343 m/s in air), v_s is the velocity of the source, f_0 is the frequency of the source, and f is the frequency heard by an observer.

a) Consider a car horn, which has a frequency of 420 Hz. If a car travelling at 80 km/hour is moving past you, what is the frequency you hear when:

i) It is moving toward you (1 mark)

ii) It is moving away from you (1 mark)

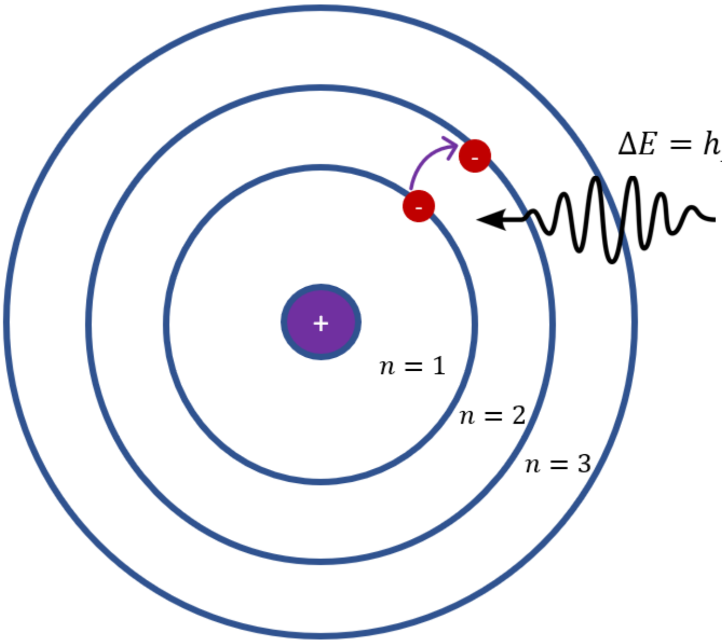
iii) Directly in front of you (1 mark)

Light behaves as a wave, so we might expect the Doppler effect to be relevant here too. Indeed it is! For observers moving at non-relativistic speeds (i.e velocities much smaller than the speed of light) the Doppler shift equation is instead given by:

$$f = \left(1 + \frac{v}{c}\right) f_0$$

b) If Earth sends a 2 GHz radio wave signal to a moving satellite, which then reflects the signal back to Earth at a frequency 3.8KHz higher, how fast is the satellite moving in the direction of radio wave propagation? (3 marks)

2. A simple model of an atom consists of electrons orbiting a positively charged nucleus. Quantum mechanics predicts that this arrangement results in shell structure for the orbiting electrons, where these electrons can only occupy discrete energy levels. The spacings and positions of these levels are specific to each element.

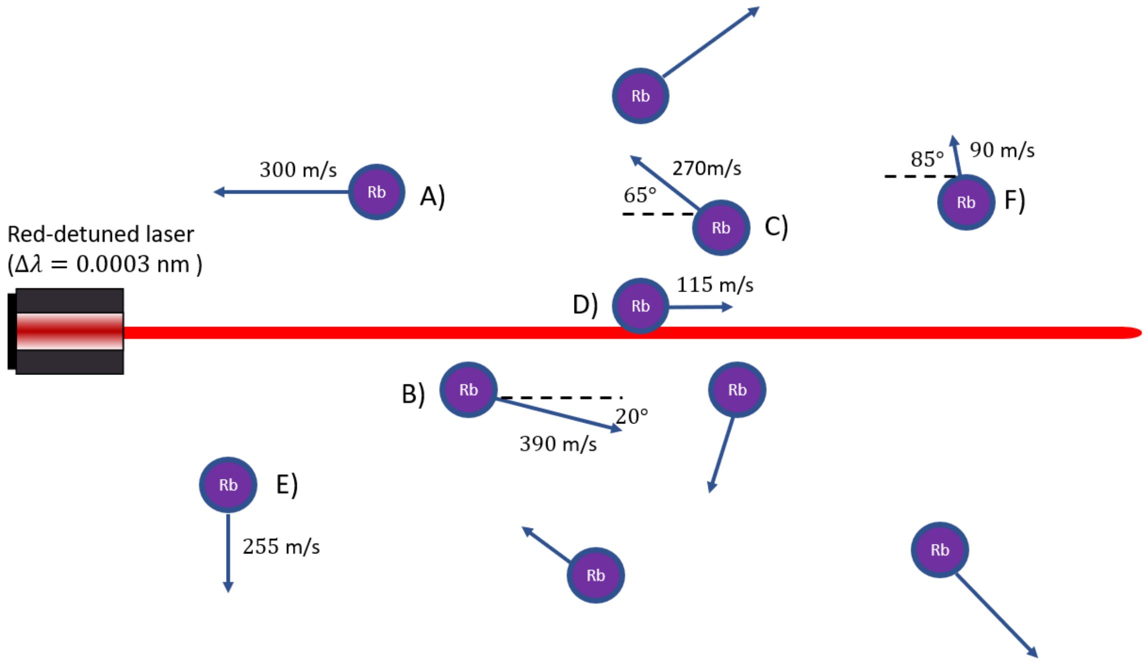


Incoming photons can excite electrons in these shells to higher-lying shells, only if the photon has an energy which exactly matches the energy spacing between the levels. This is shown above, where n denotes the energy level. Because only specific photon energies excite certain transitions, knowledge of transition spectra allow us to uniquely identify elements. The reverse process can also occur: after an electron has been excited, it will decay to the original level and emit a photon with this energy difference. However, the atom stays in the excited state for some period of time before decaying.

a) There is also further energy level structure within each shell. Consequently, there can be transitions associated with this structure. For rubidium-85, transitions within the n=5 energy level can be excited with photons of wavelength 780.0 and 794.8 nm. Using this information, calculate the energies of these photons in eV. (3 marks)

Physicists can 'tune' (slightly increase or decrease) the wavelength of a laser, so that atoms with certain velocities are more likely to be absorbed. Red detuning refers to making the laser wavelength slightly longer (redder), while blue detuning makes the wavelength shorter (bluer).

b) If we have a 780.00000 nm laser that is red-detuned such that $\Delta\lambda = 0.0003$nm, which atom will have the highest probability of absorbing this light? Explain how you have determined your selection. (4 marks)



Section E: Unusual Physics

Suggested time: 18 minutes

Question 1
Dimensional analysis is a process used which allow physicists to determine the form of an equation by considering the units of each term. In every equation in physics the dimensions (units) on the left side of the equation must equal the dimensions on the right side of the equation. Terms which are summed together must also have the same dimensions.
This means that you can use an equation to determine the equivalence of different SI units. For example, knowing the equation $F = ma$, you can determine that the units of force (Newtons) must be equal to the units of mass (kilograms) multiplied by the units of acceleration (meters per second squared). Therefore 1 Newton must be equal to 1 kg m/s/s.
The following sub parts of this question may be attempted in any order.

A very unusually shaped object of surface area A (m^2), moving through a fluid with velocity v (m/s), has been predicted to experience a drag force F (kg m/s/s) according to the following formula:

$$F = av + bAv^2 + \frac{cv}{A+d}$$

Where a, b, c and d are unknown constants.

Find the units of the unknown constants a, b, c and d in this equation. Express these in terms of the SI base units: kg (kilograms), m (meters), s (seconds). (4 marks)

Question 2
A tall building has not been designed to withstand shaking from an earthquake. When shaken with a regularly repeating force of magnitude F_0 (Newtons) and of frequency f (Hertz) the top of the building shakes with an amplitude A (meters) given by the following equation:

$$A = \frac{F_0}{\sqrt{m^2(f - f_0)^2 + b^2f^2}}$$

f_0 is called the resonant frequency of this building.

Describe what will happen to the amplitude of shaking in the building when:

a) The frequency gets very close to the resonant frequency (1 mark)
b) When the frequency is very large (1 mark)
c) When the frequency is very small (1 mark)

Alice suggests attaching a large pendulum to the top of the building that would hang on the inside of the building and be free to shake. This would change the amplitude of the top of the building to:

$$A = \frac{F_0}{\sqrt{m^2(f + f_0)^2 + b^2f^2}}$$

d) Would adding this pendulum reduce the shaking of the large pendulum for any frequencies? If so, for which frequencies would this be most effective. Justify your answer. (1 mark)

Question 3

A synchrotron is a large machine which stores a beam of fast-moving electrons in a circular ring. As the electrons move around the ring they release radiation, which can be used in a number of scientific experiments. These include determining the chemical structure of cocoa butter used to make chocolate.

A segment of a synchrotron called an undulator is used to make the electrons wiggle in their path causing them to release radiation. Bob has a theory that the power P of the radiation released by electrons in an undulator is depends on five quantities:

- q – the charge of the electrons measured in Coulombs (C)
- m – the mass of the electrons measured in kilograms (kg)
- v – the speed of the electrons measured in meters per second (m/s)
- ε_0 – a constant given by $8.85*10^{-12}$ $s^2C^2/kg/m^3$

Note P is the power measured in Watts (W). Note that a Watt can be expressed as kg m^2/s^3

Bob's theory states that

$$P = q^a m^b {\varepsilon_0}^c v^d$$

Determine the values of a, b, c and d in this equation. Please show your working, you may upload this as a photo. (4 marks)

END OF EXAM