PHYSICS: Solutions

2013 Australian Science Olympiad Exam

Time Allowed:

Reading Time: 10 minutes

Examination Time: 120 minutes

INSTRUCTIONS

- *Attempt ALL questions in both sections of this paper.*
- Permitted materials: a *non-programmable, non-graphical* calculator, blue and black pens, lead pencils, an eraser, and a ruler. **A lead pencil is essential. Ask for one if you do not have one.**
- Answer SECTION A on the MULTIPLE CHOICE ANSWER SHEET provided.
- Answer SECTION B in the answer booklet provided. Write in pen and use pencil only for diagrams, graphs and experimental work.
- You may attempt the questions in Section B in any order. Make sure that you label which parts are for which questions.
- **Do not write on this question paper. It will not be marked.**
- Do **not** staple the multiple choice answer sheet or the writing booklet to anything. They must be returned as they are.
- Ensure that your diagrams are clear and labelled.
- All numerical answers must have correct units.
- Marks will not be deducted for incorrect answers.

MARKS

Section A	10 multiple choice questions	10 marks
Section B	4 written answer questions	55 marks
		65 marks

SECTION A: MULTIPLE CHOICE
USE THE ANSWER SHEET PROVIDED

Throughout, take the acceleration due to gravity to be $9.8\ \mathrm{m\,s^{-2}}$.

Question 1
When an incandescent light bulb has a current passing through its filament the filament heats and its resistance increases. If the light bulb is connected to a constant voltage source:

a. the resistance increases at a roughly constant rate and the current through the light bulb decreases correspondingly.
b. the resistance increases at a roughly constant rate and the current through the light bulb increases correspondingly.
c. the resistance increases but the current remains the same.
d. the resistance increases at a decreasing rate and the current increases at a decreasing rate until they are both roughly constant.
e. the resistance increases at a decreasing rate and the current decreases at a decreasing rate until they are both roughly constant.

Solution: e. the filament will heat most rapidly at first and then at a decreasing rate until it reaches a steady state. Hence the resistance will do the same. The current must decrease as the resistance increases as $V = IR$ and V is constant.

Question 2
Which of the following is the best estimate of the speed of a parrot flying?

a. $3 \times 10^{-3}\ \mathrm{m\,s^{-1}}$
b. $1 \times 10^{-1}\ \mathrm{m\,s^{-1}}$
c. $3 \times 10^{0}\ \mathrm{m\,s^{-1}}$
d. $1 \times 10^{2}\ \mathrm{m\,s^{-1}}$
e. $3 \times 10^{3}\ \mathrm{m\,s^{-1}}$

Solution: c. parrots fly much faster than people walk, which rules out a. and b. which are both less than $1\ \mathrm{m\,s^{-1}}$. However, they do not fly as fast as 100 m, which is a typical length of an oval, in 1 s, which rules out d. and e.

Question 3
When a screw is very tight the most effective way to loosen it is by:

a. using a screwdriver with a fat handle and pushing down hard while turning to increase the grip.
b. using a screwdriver with a fat handle and not pushing down too hard in case you deform the screw head.
c. using a long screwdriver so that you are applying the force a long way from the point of contact.
d. using a short screwdriver with a thin handle so that you are applying the force as close as possible to the point of contact.
e. None of the above. A spanner is a more appropriate tool.

Solution: a. pushing down increases the magnitude of the contact forces (both normal forces and frictional forces) and having a fatter handle means that the same force results in a greater torque about the central axis of the screw.

Question 4
Kate has a bucket of ice cream and wants to take it on a long car trip into the desert, so she wraps it in a jumper. Is this a good idea? Choose the best answer.

a. No. The jumper will make the ice cream hotter.
b. Yes. The jumper will hold the cold in the ice cream.
c. No. The jumper always moves the cold to outside it.
d. Yes. The jumper will prevent the heat getting to the ice cream.
e. No. The jumper won't make any difference to what happens to the ice cream.

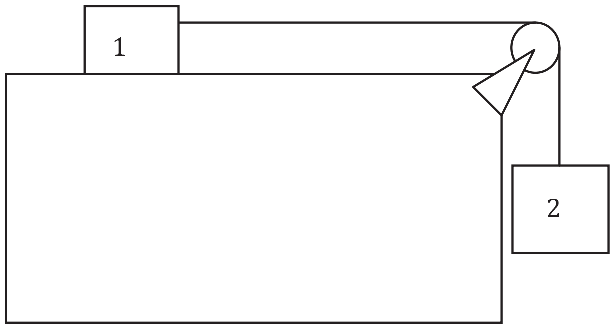
Solution: d. the jumper is an insulator and prevents the flow of heat from the warm surroundings into the cold ice cream.

Question 5
Which of the following is the best estimate of the mass of a 3D model aeroplane which is 20cm long and made of formed sheet aluminium?

a. 0.5 g
b. 5 g
c. 50 g
d. 500 g
e. 5 kg

Solution: c. the answer can be arrived at by comparing with known masses, e.g. it would be much lighter than a 500ml bottle of water, so its mass would be much less than 500 g. Also it would be much heavier than a sheet of A4 printer paper which has a mass of 5 g.

Question 6
Two blocks are connected as shown. Block 1 has mass 5 kg and is on a frictionless, horizontal surface. Block 2 has mass 8 kg and is attached to block 1 by a rope with negligible mass, passing over a frictionless pulley. What is the acceleration of block 2?



a. $15.9\ \mathrm{m\,s^{-2}}$
b. $9.8\ \mathrm{m\,s^{-2}}$
c. $6.0\ \mathrm{m\,s^{-2}}$
d. $3.8\ \mathrm{m\,s^{-2}}$
e. $0\ \mathrm{m\,s^{-2}}$

Solution: c. the total force on the system is $m_1 g$ which results in an acceleration of $m_1 g/(m_1 + m_2) = 6.0\ \mathrm{m\,s^{-2}}$.

Question 7
A shark, with a sucker-fish attached, is swimming at constant speed looking for prey. Under these conditions:

a. there is zero nett force on both the shark and the sucker-fish.
b. the nett force on the shark is greater than the nett force on the sucker-fish because the shark has a larger mass.
c. the swimming shark experiences a nett force but the sucker-fish does not because it is holding on.
d. the nett force on the shark is always the same as that on the sucker-fish because they always have the same speed.
e. the drag from the sucker-fish on the shark means that the nett force on the shark is less than on the sucker-fish.

Solution: a. as the velocity of each is constant the force on each must be zero.

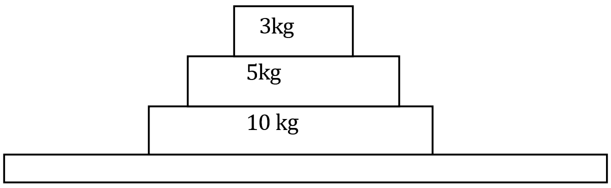
Question 8

The shark, with a sucker-fish still attached, spots a possible meal and accelerates suddenly towards it. Under these conditions:

a. there is zero nett force on both the shark and the sucker-fish.
b. the nett force on the shark is greater than the nett force on the sucker-fish because the shark has a larger mass.
c. the swimming shark experiences a nett force but the sucker-fish does not because it is holding on.
d. the nett force on the shark is always the same as that on the sucker-fish because they always have the same speed.
e. the drag from the sucker-fish on the shark means that the nett force on the shark is less than on the sucker-fish.

Solution: b. as the sucker-fish is attached to the shark they have the same acceleration. Since $\Sigma\mathbf{F} = m\mathbf{a}$ the force on each is proportional to its mass.

The blocks shown in the figure below are on a table. What is the nett force acting on the 5 kg block when the stack is:



Question 9

at rest?

a. 29.4 N downwards
b. 49 N downwards
c. 78.4 N downwards
d. 0 N
e. 19.6 N upwards

Solution: d. the block is not accelerating.

Question 10

being pushed to the right with constant velocity?

a. 29.4 N downwards
b. 49 N downwards
c. 78.4 N downwards
d. 0 N
e. 49 N to the right

Solution: d. the block is still not accelerating.

SECTION B: WRITTEN ANSWER QUESTIONS
USE THE ANSWER BOOKLET PROVIDED

Note: Suggested times are given for section B as a general guide only. You may take more or less time on any question – everyone is different.

Question 11

Suggested Time: 20 min

This question explores the characteristics of shadows formed by a variety of light sources.

Throughout this question you will be asked to draw diagrams as part of your answer. Where instructed please use the boxes on pages 2–3 of the answer booklet to draw these diagrams. Label all diagrams.

a) Point light sources emit light in all directions from a single point. They have no measurable size.

   (i) In the answer box on page 2 of the answer booklet, an object is drawn in front of a point light source. In this box draw a diagram of how the shadow forms, and what the shadow looks like on the screen.

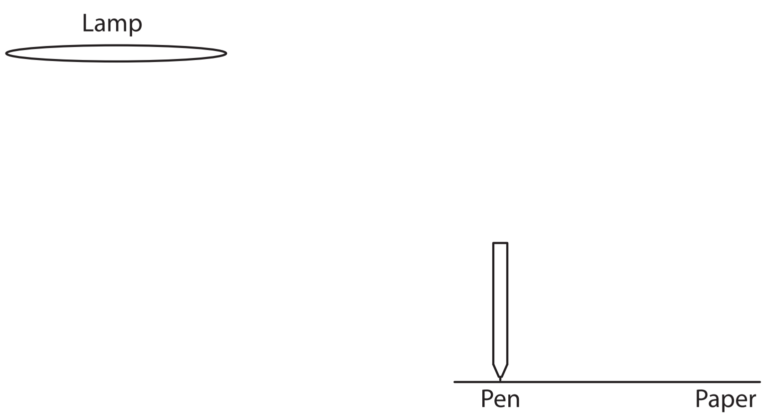
   (ii) If the object were at a distance from the light source of 1/3 the distance from the light source to the screen, how large would the shadow be compared to the object? Explain your answer using diagrams drawn in the box on page 2 of the answer booklet. Put any words needed in or near this box.

b) All real light sources, including the Sun and artificial sources, are extended sources rather than point sources. For example, at sunrise and sunset is it possible to see that the Sun is an extended source of light, circular in shape. Light is emitted in all directions from each part of an extended source.

   (i) Draw a diagram of how the shadows form and what the shadows of the object look like on the screen in front of an extended light source for the two set ups drawn in the answer box on page 2 of the answer booklet.

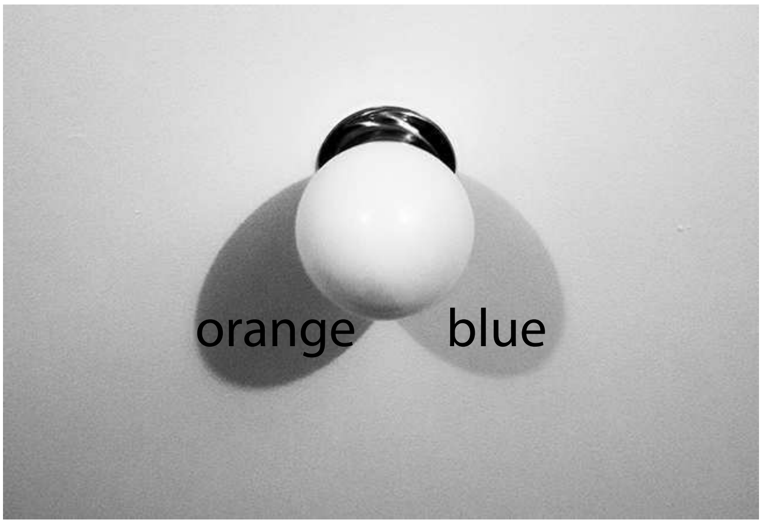
   (ii) Explain why shadows can be fuzzy-looking in the box on page 2 of the answer booklet.

   (iii) Given the setup below, draw the shadow of the pen on the diagram in the box on page 3 of the answer booklet.



c) Compact fluorescent light bulbs come in a range of slightly different colours. Some are described as 'cool' white and emit light which is more blue in colour, while others, described as 'warm' white, emit light of a more orange colour.

A room is lit by one or more lamps fitted with compact fluorescent bulbs. A shadow pattern forms on the ceiling near a ceiling lamp which is not turned on, as shown in the diagram below.



(i) Mark on the floor plan on page 3 of the answer booklet the positions of any operating lamps and the colours of their bulbs.

(ii) In the box on page 3 of the answer booklet, draw a diagram showing how the ceiling would appear from the door of the room. Indicate the colours of all regions of shadow.

d) A sheet of black cardboard with a very small round hole in its centre is held 10 cm above a white paved area outside at noon under a clear sky, and the image below is observed.

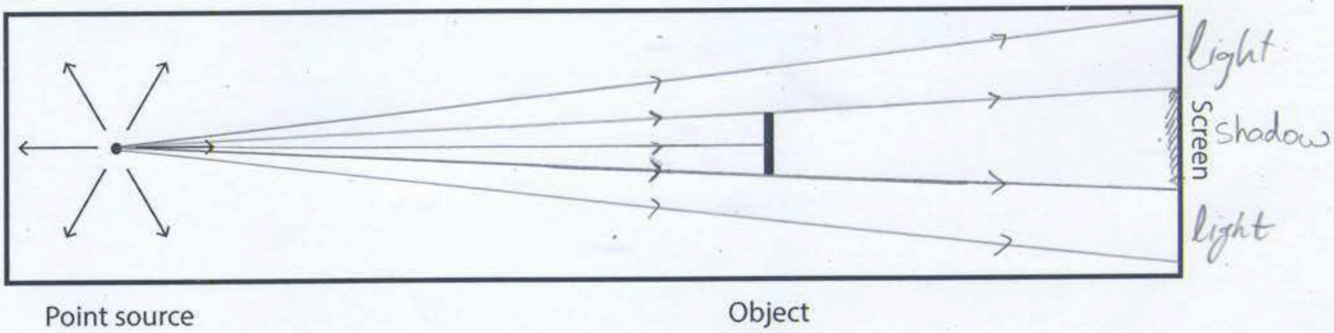
(i) Draw diagrams to explain how this image is formed in the box on page 3 of the answer booklet.

(ii) Would you expect to see the same thing on most other clear days? Explain why or why not in the box on page 3 of the answer booklet.

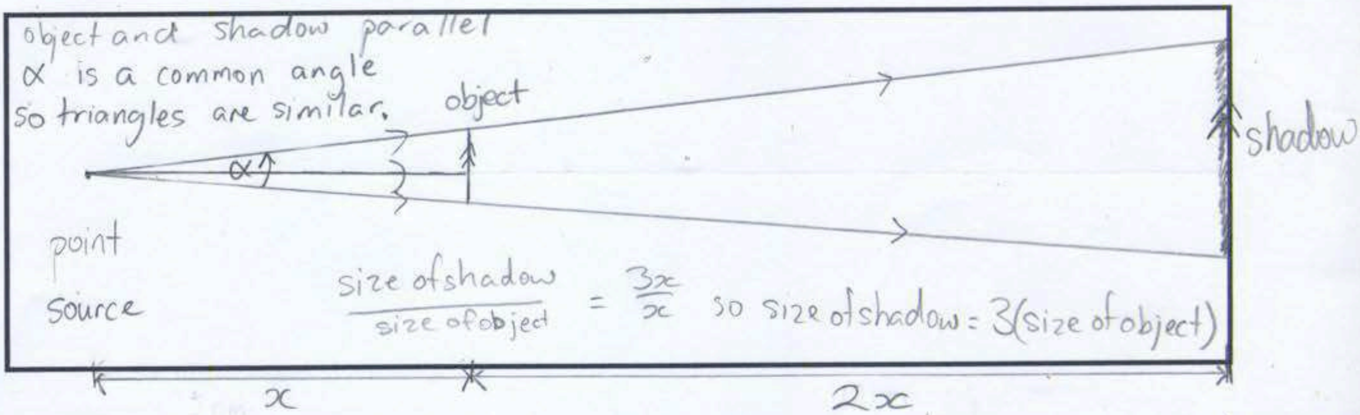
Solution:

Question 11

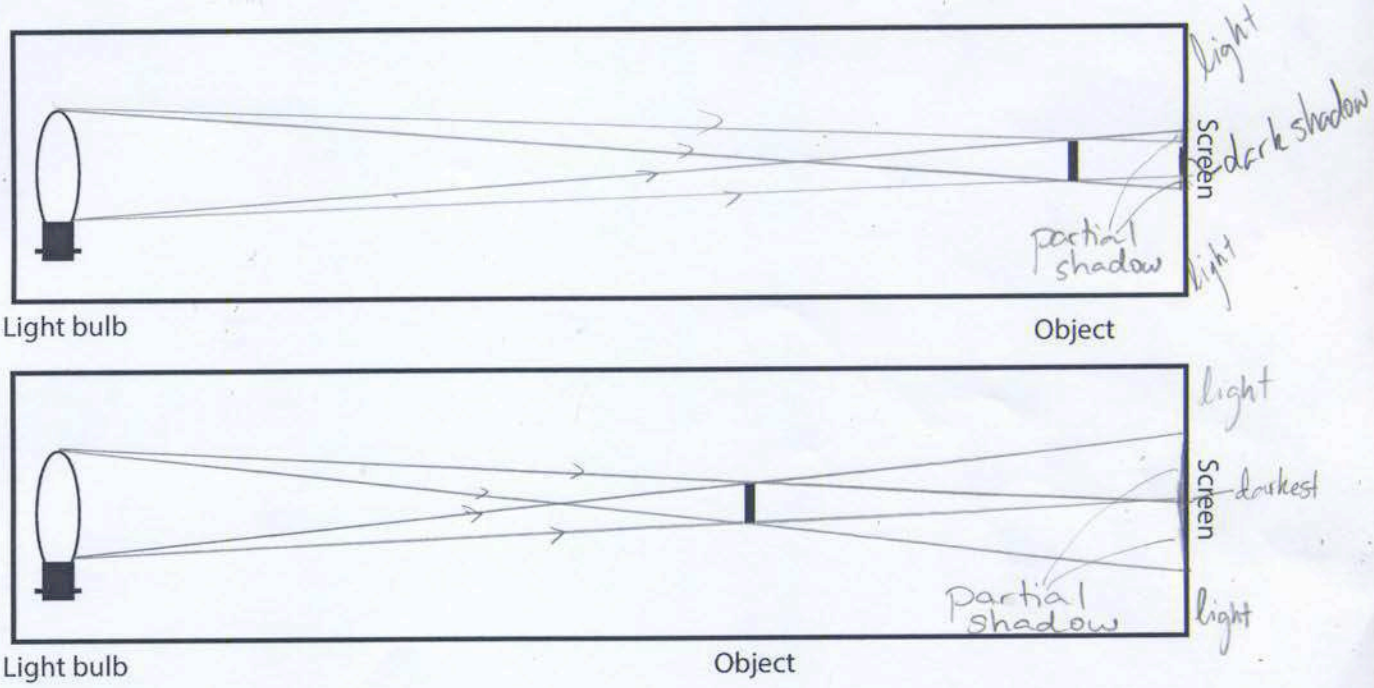
a)(i)



a)(ii)



b)(i)

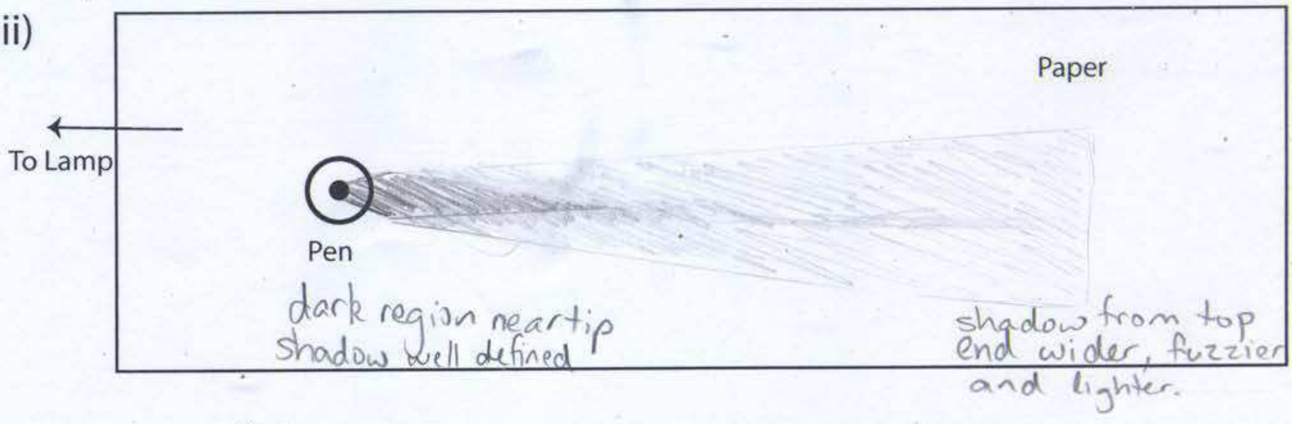


b)(ii)

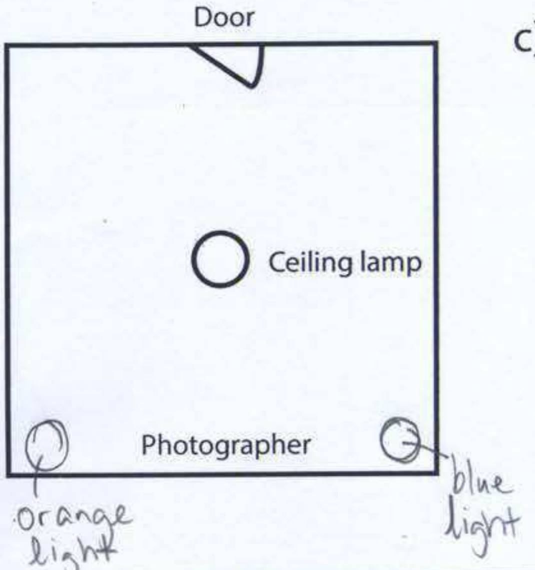
When the light source is extended there are regions of partial shadow at the edges of the shadow. These partial shadow regions make the shadows look fuzzy.

Question 11

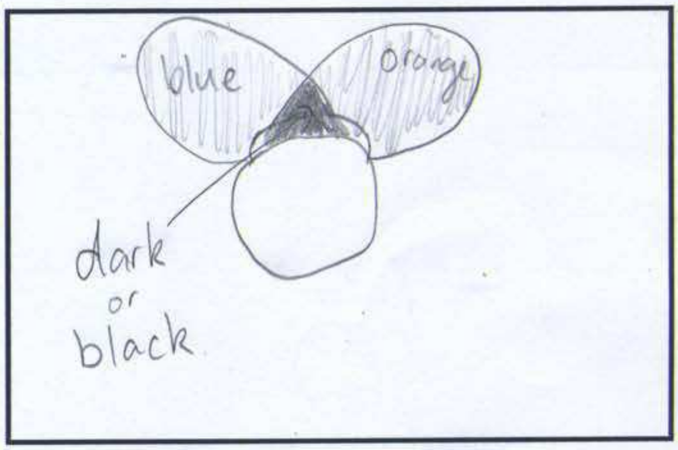
b)(iii)



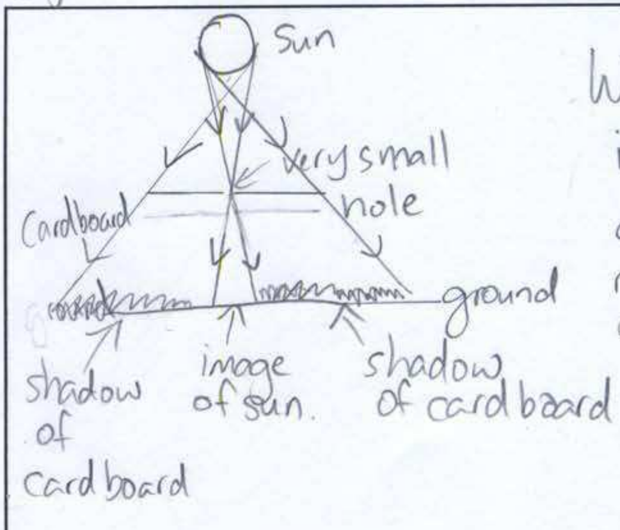
c)(i)



c)(ii)



d)(i) & d)(ii)



Would expect a circular image of the Sun on a normal clear day. not the crescent shape shown, as the Sun is a circular light source.

Marker's comments:

a) Most students were able to draw the first diagram correctly but many had difficulty with the logic in part (ii).

b) Many students had difficulties in identifying the regions where the partial shadow began and ended. Especially in part (i) it was clear that many students were not drawing accurate diagrams. While most students were able to give at least a partial explanation for (ii) they were not able to use their understanding to draw a reasonable diagram for (iii). A range of answers were accepted for (iii) as long as they were consistent with the diagram in the question and self-consistent full marks were awarded.

c) Students had difficulty with the idea that a blue shadow meant that there must be a source of blue light illuminating that region. In part (ii) many students did not realise that there would be a region of overlap between the two shadows.

d) Many students focussed their answers on why the image had a crescent shape rather than how the image was formed. All the explanation required was that the image was an image of the Sun and a statement that the sun is usually a circular source of light.

Question 12

Suggested Time: 20 min

Some elements have radioactive isotopes (radioisotopes) which can be used for medical imaging. A radioisotope is injected into the bloodstream, whence it is taken up by organs in the body. Areas of extremely high cell growth or repair such as tumours take up and retain this isotope much more efficiently than any other tissue. Thus imaging using radioisotopes can be used to indicate malignant tissue growth. Technetium-99m (^{99m}Tc) is one such radioisotope, which is used for imaging organs such as the thyroid, liver, kidneys, and brain. The half-life, the interval during which the number of atoms left of a radioisotope halves, of ^{99m}Tc is $\tau_{1/2} = 6.01$ hours.

Rates of radioactivity can be measured in Curies (Ci), equivalent to 3.7×10^{10} decays per second. For any radioisotope, the number of atoms, half-life and radioactivity are related by the formula

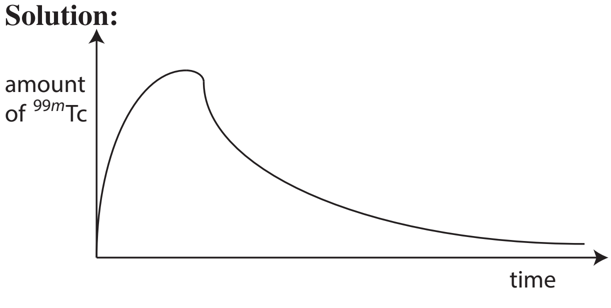
$$\text{(number of atoms)} = \frac{1}{\ln 2}\text{(half-life in seconds)} \times \text{(activity in decays per second)}.$$

In this question, we examine a model of the process of ^{99m}Tc uptake in a patient's cancerous thyroid glands. The patient is an otherwise healthy adult. In this model, $A = 10.0$ mCi of ^{99m}Tc is injected into a vein in the patient's arm of radius $r_a = 1.00$ mm, enters the bloodstream, then enters each thyroid gland through an artery in the patient's neck of radius $r_n = 1.70$ mm.

Let the velocities of blood flow in the patient's arm and neck be $v_a = 3.00$ mm/s and $v_n = 40.0$ cm/s. Let the total blood volume of the patient be $V = 5\text{ L} = 5 \times 10^{-3}\text{ m}^3$, and let each thyroid gland (there are two) have volume $V_t = 9$ mL. The ^{99m}Tc emits gamma rays of energy $E = 2.24 \times 10^{-14}$ J .
Give your answers both as formulae and numerically where applicable.

a) What is the concentration (in number of atoms per litre) of ^{99m}Tc in the bloodstream after the injection?
Solution: The concentration is $N/V = a\tau_{1/2}/(V \ln 2) = 2.31 \times 10^{12}$ atoms/L

b) Qualitatively, sketch the amount of ^{99m}Tc in the thyroid as a function of time, starting from the time of injection.
Solution:



c) The continuity equation in fluid mechanics states that the volume flow rate of fluid flowing through a pipe is constant. Consider the blood flow in the arm and neck of the patient - does the continuity equation hold in this model? Justify your answer with calculations, and use your knowledge of the body to explain why you would expect this result.
Solution: The flow rate through a circular pipe is $\pi r^2 v$. The flow rate in the neck, $\approx 1.2 \times 10^{-6}\text{ m}^3/\text{s}$, is much greater than the flow rate in the arm, $\approx 3.0 \times 10^{-9}\text{ m}^3/\text{s}$ so the continuity equation does not hold. As the systems of blood vessels is complex with many different vessels connected meaning that the vein in the arm and the artery in the neck are not part of the

same continuous pipe this continuity equation would net be expected to hold.

d) What is the initial rate of energy release due to gamma radiation emitted from a thyroid gland? In this and subsequent parts you may neglect the time taken for the thyroid glands to saturate with ^{99m}Tc.
Solution: The initial rate is $-\Delta E/\Delta t = EA = 8.30 \times 10^6$ J s^{-1}

e) A scan is taken over $t_s = 10.0$ minutes. If the total energy detected by the scanner exceeds $E_{\text{min}} = 5 \times 10^{-4}$ J, an image appears due to radioactivity in a thyroid gland. Approximately how much time will elapse before radioactivity is no longer detected in a scan?
Solution: It is reasonable to treat the activity as constant over the 10 minutes required for a scan as this is much shorter than one half-life. In the first ten minutes the energy released is 5.0×10^{-3} J which is 10.0 times the lower limit. In three half-lives, i.e. 18 hours, the level will reach 1.25 times the minimum, and after a fourth half-life the level will be 0.75 times the minimum. Hence the time will be around 20-21 hours.
Solving exactly by knowing that the decay is exponential gives

$$t = \frac{\tau_{1/2}}{\ln 2} \ln \left(\frac{EAt_s}{E_{\text{min}}} \right) = 20 \text{ hours}$$

Marker's comments:

a) Many students did not know the meaning of the prefix milli.
Some students used 3.7×10^{10} decays per second as the activity in decays per second because they had the same units.

b) Most students sketched either the decreasing part of the curve or the increasing one but not both.

c) Many students did not understand that the product $\pi r^2 v$ was required to be constant by the continuity equation, not both r and v. Also students were incorrectly stating that because the vessels could change in radius due to contracting, dilating or being blocked with fat the continuity equation could not hold.

d) Done relatively well.

e) Most students did not realise that the energy detected in the scan was the cumulative energy released over the duration of the scan. Those who did realise this also realised that the activity is approximately constant over the duration of a scan.

Question 13

Suggested Time: 20 min

After some time spent pondering the workings of the universe, John says to Mary, "Energy is always conserved." Mary, however, doesn't agree. She says to John that if two identical cars travelling at the same speed collide head-on, there is kinetic energy before the collision, but no kinetic energy after. The two continue their disputation over a cup of tea, and await your assistance at the end of this question.

The *momentum* of an object of mass m moving with velocity $\mathbf{v}$ is

$$\mathbf{p} = m\mathbf{v} \ .$$

The (vector) sum of the momenta of all of the objects in any collision is the same before and after the collision. In this question, a positive velocity indicates motion to the right.

a) Two hard particles m and M collide head-on. They have initial velocities $\mathbf{v}$ and $\mathbf{V}$ respectively (so $\mathbf{V}$ is negative). If the collision is *elastic*, the kinetic energy is conserved, and the velocities of the particles after colliding are

$$\mathbf{v}' = \frac{(m-M)\mathbf{v} + 2M\mathbf{V}}{m+M}$$
$$\mathbf{V}' = \frac{(M-m)\mathbf{V} + 2m\mathbf{v}}{m+M}$$

(i) What do these equations become for $m = M$? Give an example of such a collision.
Solution:

$$\mathbf{V}' = \mathbf{v}$$
$$\mathbf{v}' = \mathbf{V}$$

Examples: two bouncy balls of the same mass bouncing off each other, two electrons colliding, etc.

(ii) Approximate these equations for $M \gg m$. Give an example of such a collision.
Solution: $M - m \approx M \approx m + M$, so

$$\mathbf{V}' = \mathbf{V} + 2\frac{m}{M+m}\mathbf{v}$$

Note that the last term is small compared to the first unless $\mathbf{V} \ll \mathbf{v}$.

$$\mathbf{v}' = -\mathbf{v} + 2\mathbf{V}$$

Examples: a bouncy ball bouncing off the Earth, a proton and a electron colliding, etc.

b) Find the fraction of the kinetic energy which is lost if two gunky blobs of masses $m = 0.50$ kg and $M = 3.0$ kg with velocities $\mathbf{v} = 0.50\ \mathrm{m\,s^{-1}}$ and $\mathbf{V} = -0.10\ \mathrm{m\,s^{-1}}$, collide head-on and the final velocity of the gunky blob with mass m is $\mathbf{v}' = -0.25\ \mathrm{m\,s^{-1}}$.

Solution: Here momentum is conserved but energy is not because the blobs are gunky rather than hard. Hence,

$$M\mathbf{V} + m\mathbf{v} = M\mathbf{V}' + m\mathbf{v}'$$

and $V' = 0.025\ \mathrm{m\,s^{-1}}$. The kinetic energy is calculated using $K = mv^2/2$ to be initially $K_i = 0.078$ J and finally $K_f = 0.017$ J so 78% of the kinetic energy is lost.

c) In the case where the collision is completely inelastic, the gunky blobs stick together to form a superblob of total mass $M' = (M+m)$. If $m = 0.50$ kg, $M = 2.5$ kg, $\mathbf{v} = 0.50\ \mathrm{m\,s^{-1}}$ and $\mathbf{V} = -0.10\ \mathrm{m\,s^{-1}}$, determine the fraction of kinetic energy lost during the formation of the superblob.

Solution: The initial total momentum of the system is $M\mathbf{V} + m\mathbf{v} = 0$. This means that the final velocity of the superblob is also zero. The initial kinetic energy is $K_i = 0.075$ J and 100% is lost in the collision.

d) Is either John or Mary from above correct, and how can their statements be reconciled?

Solution: John is correct that energy is always conserved but it can be converted to other forms, such as thermal energy. Mary is correct that kinetic energy is not conserved.

Marker's comments:

a) (i) Mostly completed well but some students did not substitute $m = M$ in the denominator.
   (ii) Most students found this more difficult, credit was given to the many students who obtained $V' = V$. Many examples given were of inelastic collisions.

b) Few students realised that the larger mass was still moving after the collision. Some students calculated the energy retained rather than lost. Many students treated the collision as elastic which is not the case. Many students made sign errors.

c) Generally better completed than (b), as no final data were given students felt the need to calculate final velocities. Some students continued to incorrectly apply the equations from (a).

d) Generally correctly answered however students needed to give very clear explanations for full marks to be awarded.

There was some confusion about the differences between momentum, energy, force and kinetic energy.

Question 14

Suggested Time: 40 min

Friction is the force between surfaces that acts to prevent their relative motion. It acts along the plane of the surface. The part of the contact force which acts perpendicular to the plane of the surface is the normal force. Static friction, present when two bodies are at rest relative to each other, takes any value necessary to balance other forces up to a maximum given by

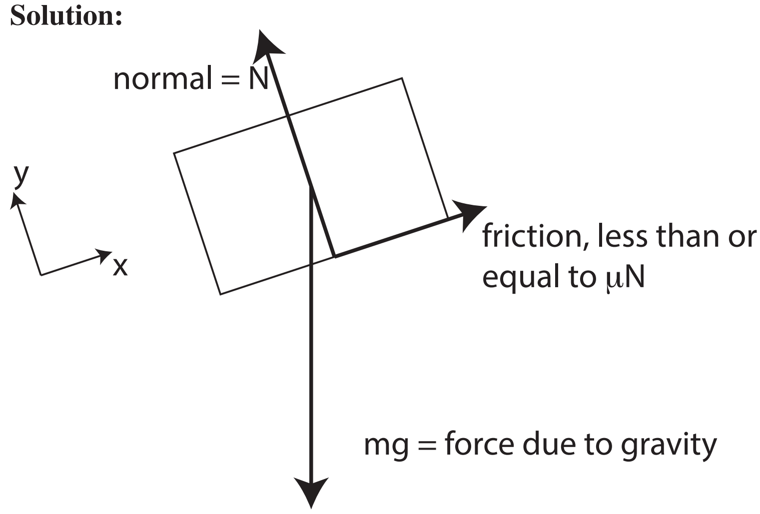
$$\mathbf{F} = \mu \mathbf{N} \quad ,$$

where μ is the *coefficient of static friction*.

Friction can be used to make eating pineapple an exciting experience. Consider a large cube of pineapple sitting on a chopping board. One end of the board is on the edge of the bench, and the other end is raised, so that the board is inclined at an angle θ to the bench.

a) Draw a free body diagram showing the forces acting on the pineapple.

Solution:



Marker's comments:
Students often included things other than forces in their diagrams. They also did not always label the forces in the diagram or indicate where on the body the force acted.

b) The board is gradually tilted up until the cube of pineapple begins to slide inexorably toward the waiting mouth at bottom of ramp. Show that $\mu = \tan\theta$.

Solution:
Resolve to the force due to gravity into components along and perpendicular to the ramp, i.e. into the *x* and *y* directions shown in the diagram above. In combination with Newton's second law, the condition that there is no acceleration perpendicular to the ramp gives

$$N = mg\cos\theta \quad .$$

In the direction along the ramp at the angle where the pineapple is about to slip the nett force is still zero but the frictional force takes its maximum value. Hence,

$$mg\sin\theta = \mu N \quad .$$

Solving for the frictional coefficient gives

$$\mu = \frac{\sin\theta}{\cos\theta} = \tan\theta \quad ,$$

as required.

Marker's comments:

Students needed to give more explanation of their reasoning in this part.

Students often incorrectly applied Newton's third law.

Cubes of pineapple are, regrettably, perishable goods, and we apologise that we were unable to ship one to you for the purposes of this examination. Therefore, the next part of this question will use the (admittedly poor) substitutes of paper and pencil. When you draw on paper with a lead pencil, you coat the paper with a graphite mixture.

c) The coefficients of static friction differ between different pairs of surfaces. Using the ideas presented above and the theory you have derived, devise and perform an experiment to find the *difference* between A) the coefficient of static friction between paper and paper and B) the coefficient of static friction between paper and graphite mixture.

Equipment: You may tear out the next three leaves of this question book to use as equipment. Some suggested folds are marked to help you create some useful apparatus, but the choice of what to do with your paper is up to you. Along with the paper of these three pages, you may also use the lead pencil which you brought into this exam, and a ruler. Remember to be safe when using any equipment – make sure you don't injure yourself or other people (or your pencil or ruler).

What is required: Write out the method that you are going to use in detail and justify why you have chosen it, along with any modifications you make along the way. State your results, and any processing you do of them, and evaluate your answers.

Important: *the credit in this question is primarily for your method, how you would calculate the results, and your observations of what works and doesn't as you try your experiment. The numeric answers are a small part, and you should not be concerned if you are unable to get them – we are interested in your thought processes, designs and observations.*

As a final note, although this be in lieu of a pineapple-based experiment, do not attempt to eat any of your equipment.

Solution: No solution is given as there are many variations with no clear preferred solution. Students solutions were required to have the elements requested in the question.

Marker's comments:

Students who constructed some apparatus and performed an experiment obtained a range of results, with many discussing quite interesting sources of error and modifications to their methods. Some students managed to extract quite good values for the coefficients. Common problems with this question were not attempting an experiment, attempting to find coefficients of friction between various different objects and paper, and rolling pieces of pencil lead down the paper instead of coating the paper with a layer of pencil and then using another piece of paper.

Credit was given for the method, discussions, and analysis of results, including an estimate of uncertainty. As long as the coefficients were remotely plausible the results did not have to be accurate to score the marks.

This work of ours is done: there are no questions more.
Your work has just begun: enjoy it, we implore!

The remaining pages in this booklet are for use as equipment for Q14.

This page may be torn out and used as equipment.
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Integrity of Competition

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