Physics
Higher level
Paper 3

25 October 2023

Zone A afternoon | **Zone B** afternoon | **Zone C** afternoon

Candidate session number

1 hour 15 minutes

Instructions to candidates

- Write your session number in the boxes above.
- Do not open this examination paper until instructed to do so.
- Answers must be written within the answer boxes provided.
- A calculator is required for this paper.
- A clean copy of the **physics data booklet** is required for this paper.
- The maximum mark for this examination paper is **[45 marks].**

Section A	Questions
Answer all questions.	1 – 2

Section B	Questions
Answer all of the questions from one of the options.	
Option A — Relativity	3 – 7
Option B — Engineering physics	8 – 11
Option C — Imaging	12 – 16
Option D — Astrophysics	17 – 20

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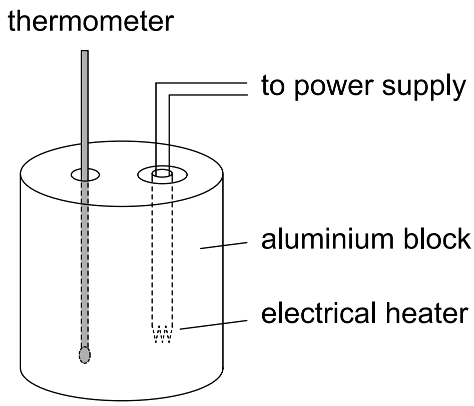
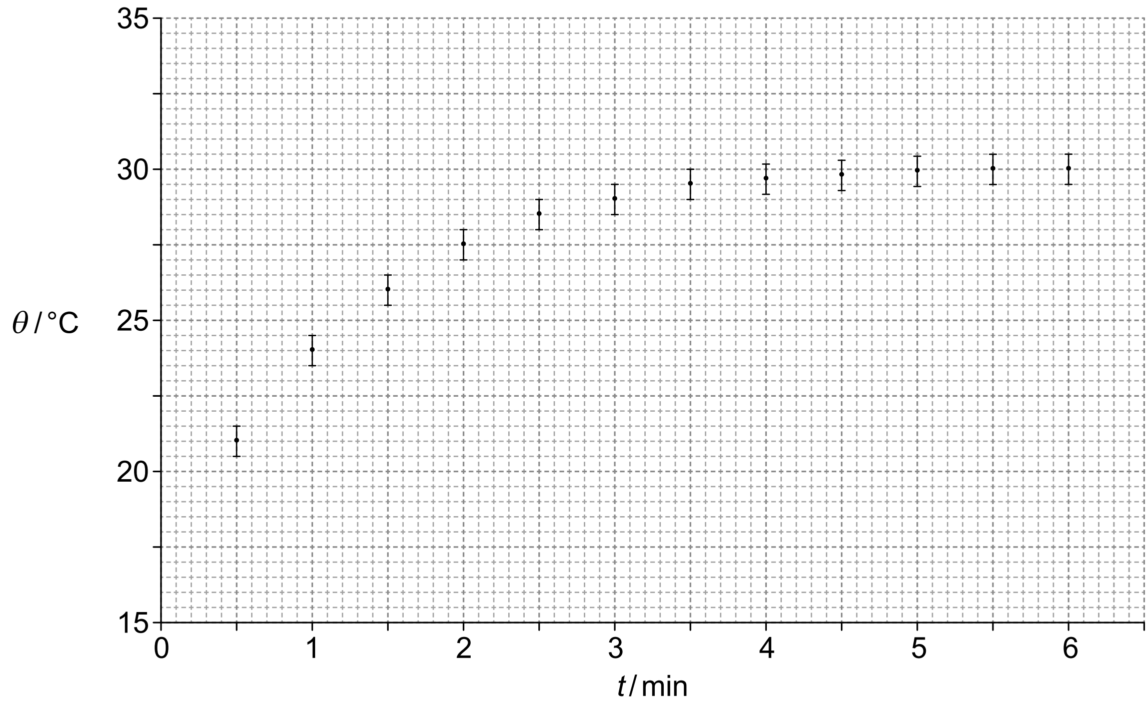
Section A

Answer **all** questions. Answers must be written within the answer boxes provided.

1. A thermometer and an electrical heater are inserted into small holes in a solid aluminium block.



The heater is turned on at time $t = 0$. The graph shows the variation of the temperature θ of the block with time t.



(This question continues on the following page)

(Question 1 continued)

(a) (i) On the graph, draw the line of best-fit for the data. [1]

(ii) Estimate the initial temperature of the block. [1]

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(b) Suggest why the temperature of the block approaches a constant value. [2]

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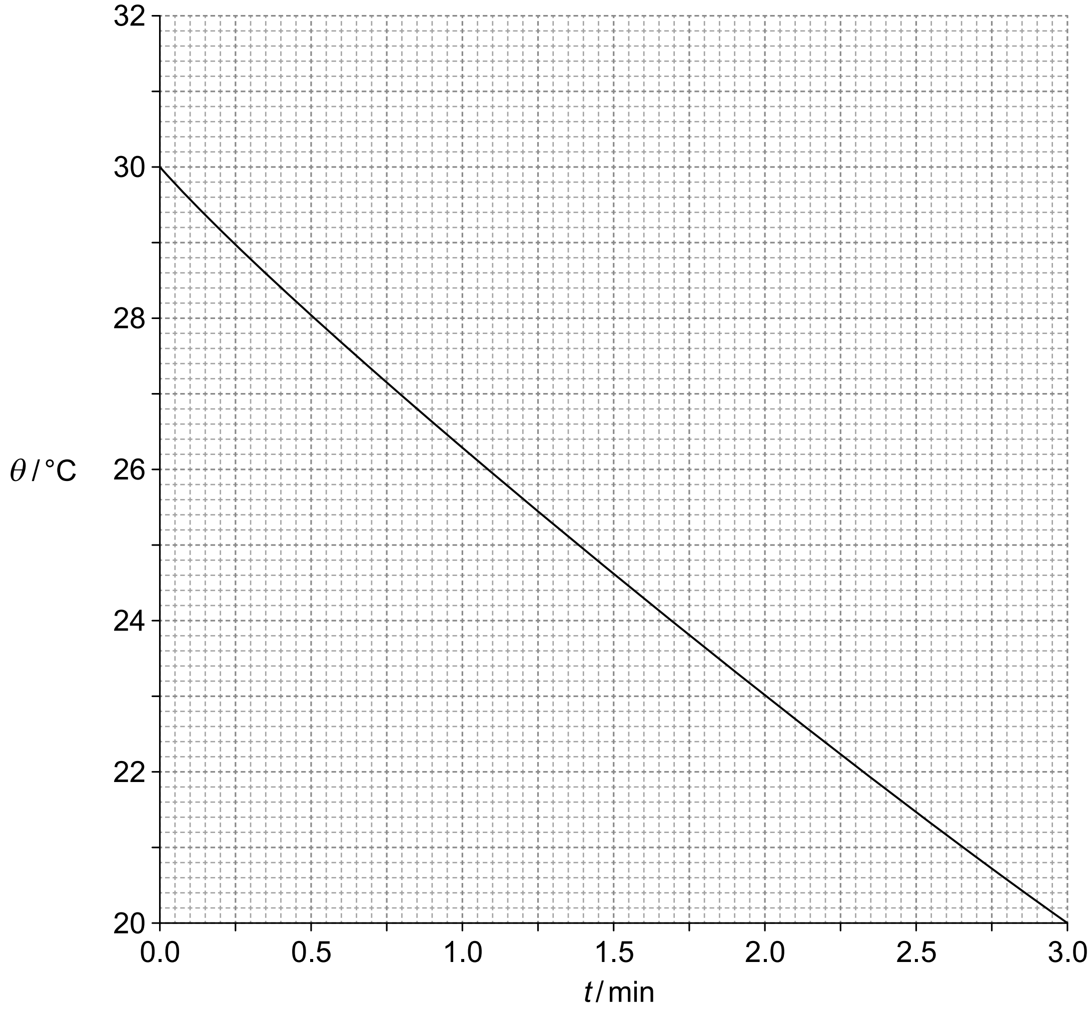
(This question continues on the following page)

(Question 1 continued)

(c) When the temperature has reached a constant value the heater is turned off. The graph shows the variation of the temperature θ of the block with time *t*.



Show that the **initial** rate of change of the temperature of the block is approximately $-4.0\,\mathrm{K\,min^{-1}}$. [2]

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(This question continues on the following page)

(Question 1 continued)

(d) The power of the heater is 52 W. The mass of the block is 0.85 kg. Determine the specific heat capacity of aluminium. [2]

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(e) The percentage uncertainty in the rate of change in (c) is 4 %. The percentage uncertainty in the power of the heater is 3 % and that in the mass of the block is 1 %.

(i) Estimate the absolute uncertainty in the specific heat capacity of aluminium. [2]

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(ii) Write down the value of the specific heat capacity of aluminium, its uncertainty and its unit. Give your answer to an appropriate number of significant figures. [1]

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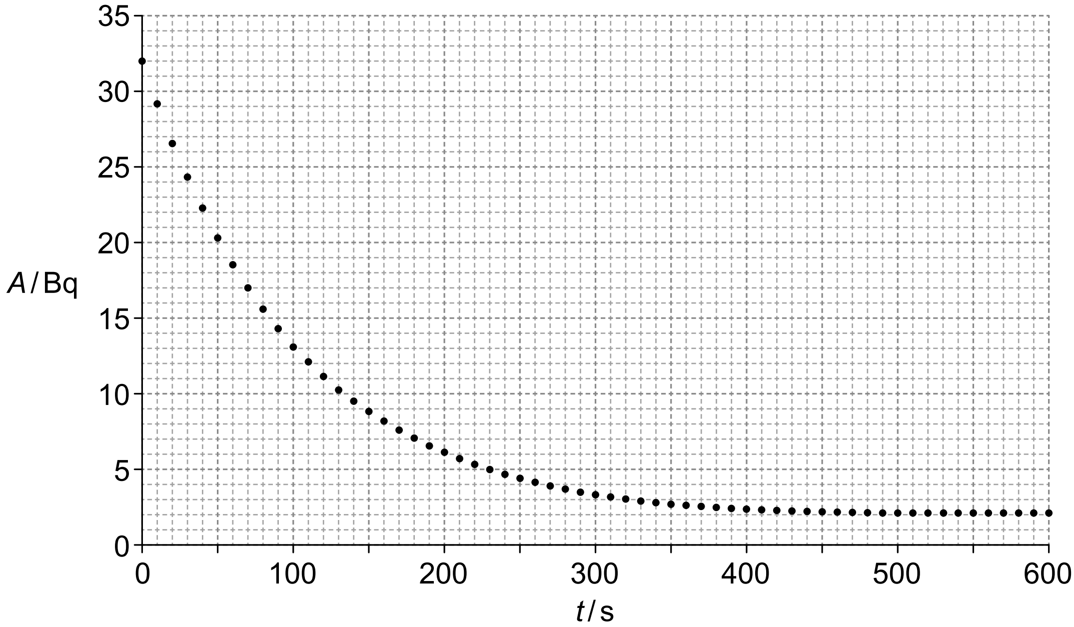
Answers written on this page will not be marked.

2. The graph shows the variation with time t of the activity A of a sample of protactinium-234.



(a) Suggest why the activity approaches a non-zero constant value. [1]

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(b) Estimate the half-life of protactinium-234 explaining your work. [3]

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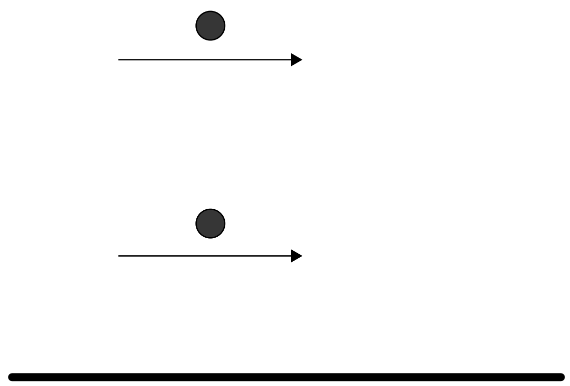
Section B

Answer **all** of the questions from **one** of the options. Answers must be written within the answer boxes provided.

Option A — Relativity

3. Two muons are moving parallel to each other with the same velocity relative to the ground.



In the frame of reference in which the muons are at rest, the force between them is a repulsive electric force.

(a) Explain, for the frame of reference of the ground,

(i) why there is an additional magnetic force between the muons. [1]

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(ii) whether the electric or the magnetic force has the greater magnitude. [2]

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(Option A continues on the following page)

(Option A, question 3 continued)

(b) In muon decay experiments, muons produced high in the Earth's atmosphere move towards the ground at speeds close to the speed of light. Detectors on the ground record the arrival of muons. Outline how these experiments provide support for time dilation. [3]

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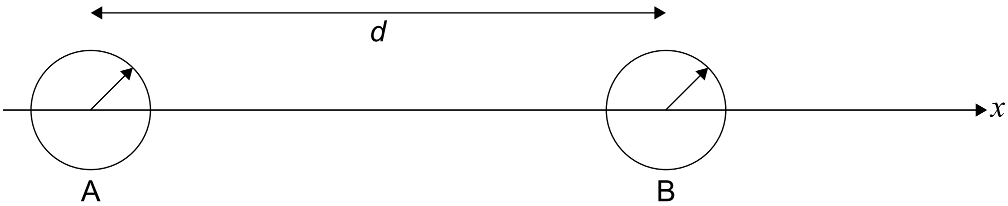
4. The diagram shows two clocks, A and B, that have been synchronized. Clock A is at the origin and clock B is a distance *d* away in the same inertial reference frame.



Suggest a way by which the clocks were synchronized. [3]

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(Option A continues on the following page)

(Option A continued)

5. A spacecraft leaves Earth with speed 0.800 c, relative to Earth, on its way to a planet that is 12.0 light years away according to Earth measurements.

(a) Calculate the time of arrival of the spacecraft at the planet according to the

(i) Earth. [1]

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(ii) spacecraft. [2]

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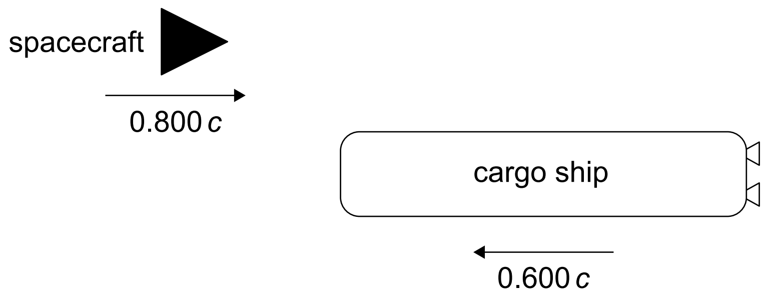
(Option A continues on the following page)

(Option A, question 5 continued)

(b) On its way to the planet the spacecraft moves past a cargo ship returning to Earth. The proper length of the cargo ship is 992 m and its speed is 0.600 c relative to Earth.



(i) State what is meant by proper length. [1]

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(ii) Show that the speed of the cargo ship relative to the spacecraft is 0.946 c. [1]

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(iii) Calculate the length of the cargo ship according to the spacecraft. [2]

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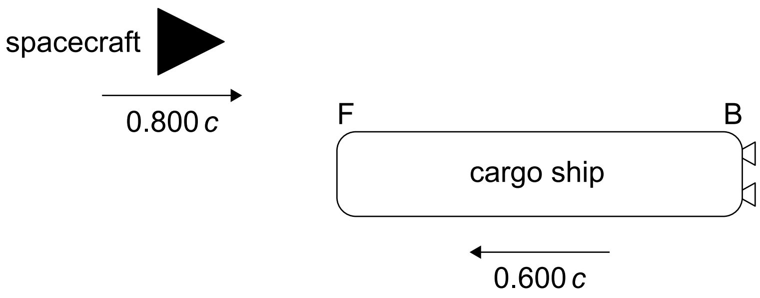
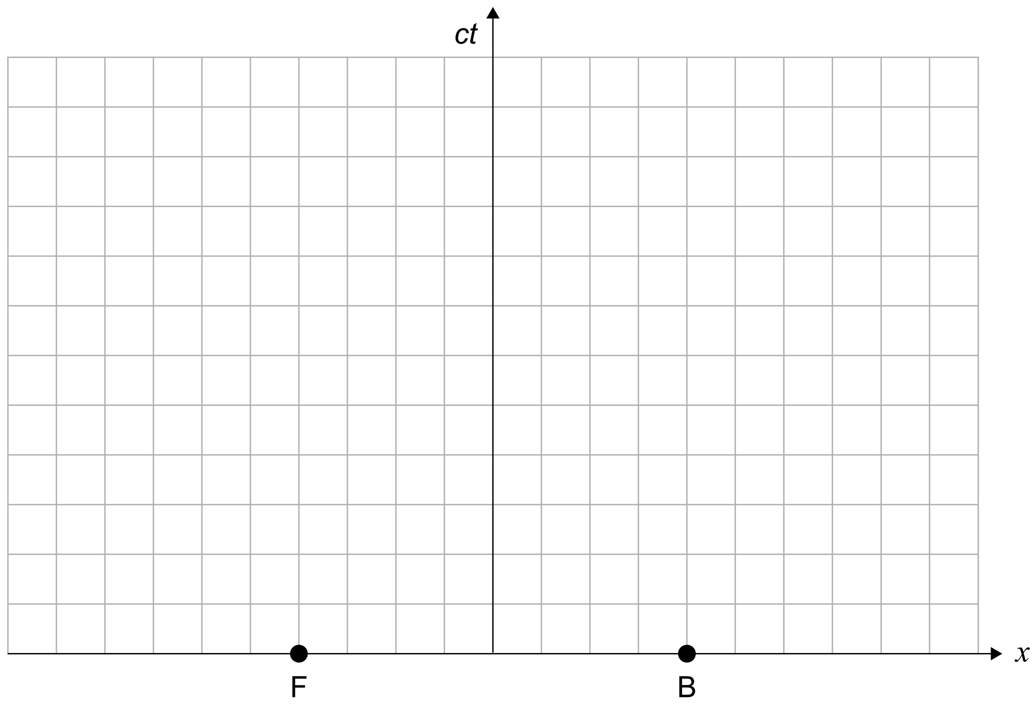
(Option A continues on the following page)

(Option A, question 5 continued)

(c) As the spacecraft approaches the cargo ship a light signal is emitted from the front of the cargo ship (F) towards the back (B).



This situation is represented in the spacetime diagram that shows the rest frame of the cargo ship. F and B represent the front and back of the cargo ship when the light signal is emitted. The scale on the axes is the same.



(Option A continues on the following page)

(Option A, question 5 continued)

(i) Construct lines on the spacetime diagram to show the arrival of the light signal at the back of the cargo ship. Label this event using the letter A. [2]

(ii) Determine the time it takes the signal to arrive at the back of the cargo ship according to the spacecraft. [2]

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6. A proton is accelerated from rest until its momentum becomes $2.50\,\text{GeV}\,c^{-1}$.

Calculate the

(a) potential difference through which the proton was accelerated. [2]

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(b) speed of the proton after acceleration. [2]

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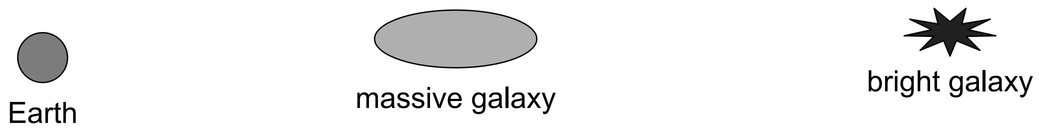
(Option A continues on the following page)

(Option A continued)

7. (a) Light from a distant bright galaxy arrives at a telescope on Earth after having travelled past a massive galaxy. Multiple images of the bright galaxy are formed.



Explain the formation of the multiple images. (You may draw a diagram to help with your answer.) [3]

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(Option A continues on the following page)

(Option A, question 7 continued)

(b) State what is meant by the event horizon of a black hole. [1]

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(c) The radius of the event horizon of a black hole is R. A probe is at a distance of $0.25R$ **above** the event horizon. The probe sends radio pulses at intervals of 1.0 s, according to the probe. Calculate the time between the arrival of the pulses at a spacecraft far from the black hole. [2]

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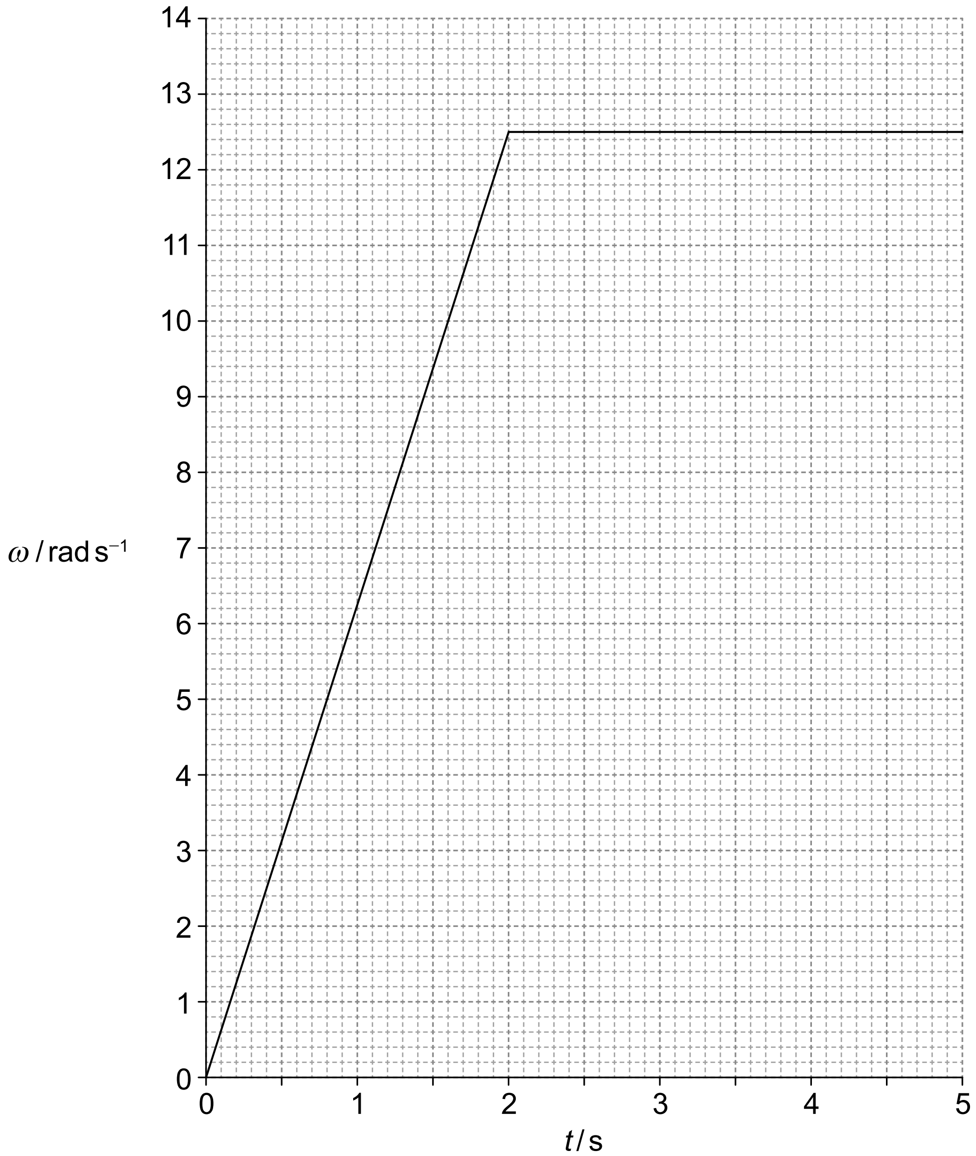
End of Option A

Option B — Engineering physics

8. A net torque acts on a horizontal disk of mass 0.20 kg and radius 0.40 m that is initially at rest. The disk begins to rotate. The graph shows the variation with time t of the angular speed ω of the disk.



The moment of inertia of a disk of mass M and radius R about a vertical axis through its centre is $\frac{1}{2}MR^2$.

(Option B continues on the following page)

(Option B, question 8 continued)

(a) Show that the angular acceleration of the disk is about 6 rad s^{-2}. [1]

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(b) Calculate the torque that acts on the disk while it accelerates. [2]

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(Option B continues on page 19)

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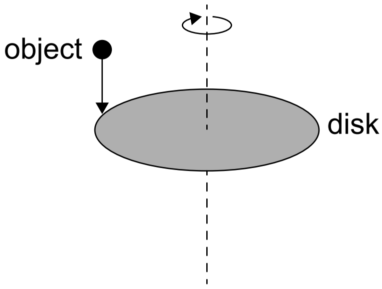
will not be marked.

(Option B, question 8 continued)

(c) While the disk is rotating at its final constant angular speed, a small object of mass 0.10 kg falls on the disk and sticks to the edge of the disk.



(i) Calculate the new angular speed of the disk. [3]

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(ii) Determine the fraction of the total energy of the disk that was lost. [3]

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(Option B continues on the following page)

(Option B continued)

9. A monatomic ideal gas is trapped in a cylinder by a piston. The following data are available.

Initial pressure of gas $= 1.00 \times 10^{5}\,\text{Pa}$

Initial temperature $= 712\,\text{K}$

Quantity of gas $= 6.00 \times 10^{-4}\,\text{mol}$

The gas undergoes an adiabatic expansion to a volume of $8.00 \times 10^{-5}\,\text{m}^{3}$.

(a) (i) Determine the pressure of the gas after the adiabatic expansion. [3]

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(ii) Determine the work done by the gas during the expansion. [3]

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(Option B continues on the following page)

(Option B, question 9 continued)

(b) The gas then undergoes an isobaric compression until its volume is equal to the initial volume.

(i) Calculate the energy removed in this isobaric compression. [3]

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(ii) The gas returns to its original state in an isovolumetric change. The energy supplied during this change is 3.9 J. Calculate the efficiency of this cycle. [1]

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(iii) Outline why it is important that engines are designed with high efficiency even though all engines obey the first law of thermodynamics. [1]

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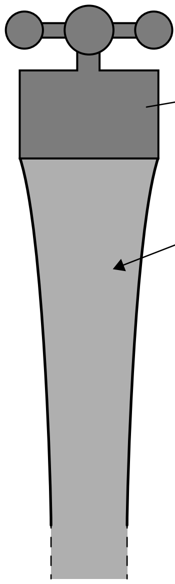
(Option B continues on the following page)

(Option B continued)

10. The diagram shows water coming out of a tap (faucet).



(a) Water leaves the tap at an initial speed of $1.2\,m\,s^{-1}$. Calculate the speed of the water when it has fallen 0.20 m. [2]

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(b) Explain why the diameter of the water stream decreases. [3]

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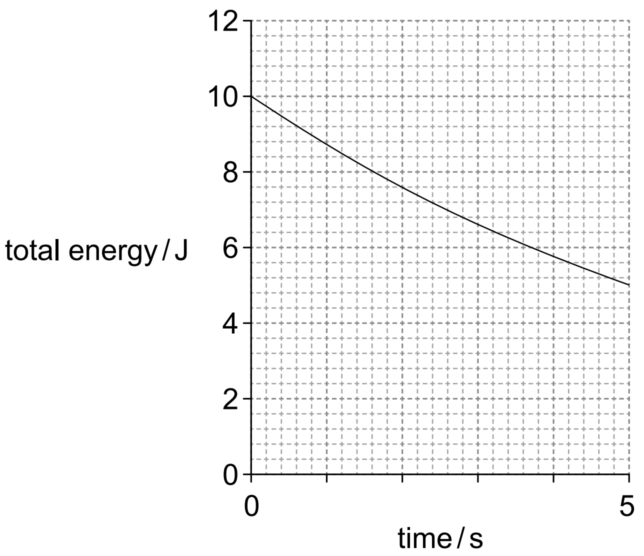
(Option B continues on the following page)

(Option B continued)

11. A mass-spring system undergoes damped oscillations with a time period of 5.0 s. At $t = 0$, the system is at maximum displacement. The graph shows the variation of the total energy of the system with time.



(a) (i) Calculate the Q factor for the system. [1]

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(ii) Draw, on the axes, a graph to show how the potential energy of the system varies with time. [2]

(b) Explain why engineers must consider resonance when designing structures. [2]

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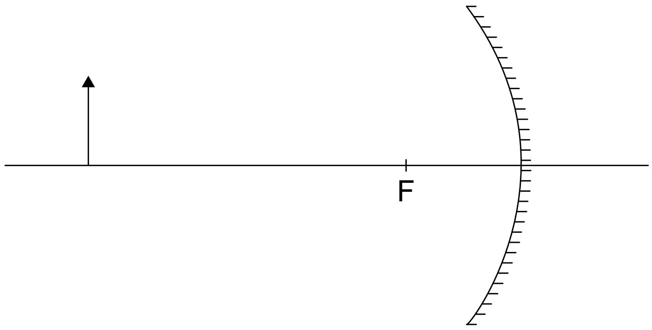
End of Option B

Option C — Imaging

12. The diagram shows an object in front of a spherical converging mirror with a focal point F.



(a) Construct a ray diagram to show the formation of the image. [2]

(b) The mirror is now moved a large distance to the right. Outline the effect of this on the magnification of the image. [2]

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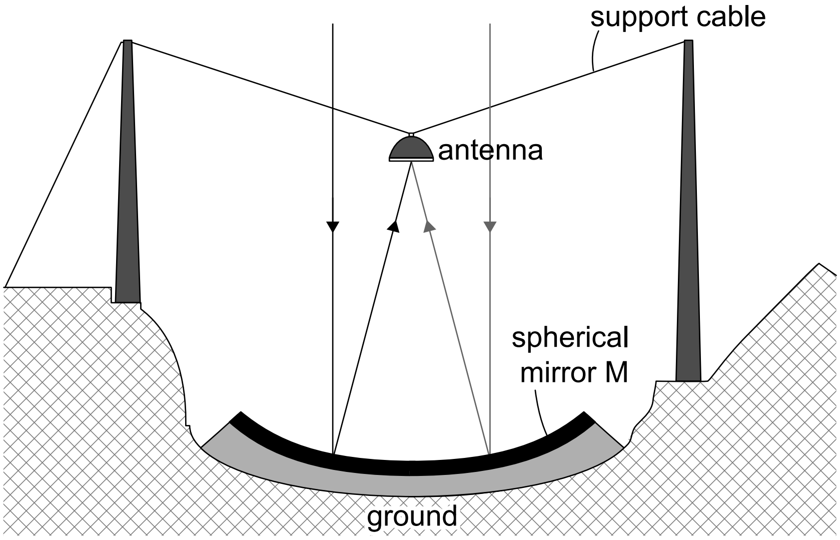
(Option C continues on the following page)

(Option C continued)

13. The single-dish radio telescope at Arecibo had a fixed spherical mirror M of diameter of 0.3 km made up of a large number of flat aluminium panels. The antenna was movable.



(a) Explain why a large number of flat panels were used to construct the fixed spherical mirror M. [1]

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(b) The telescope was mounted on the ground and could not be steered. Explain how, for one position of the Earth, the radio telescope could gather information from different parts of the sky. [2]

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(Option C continues on the following page)

(Option C, question 13 continued)

(c) Scientists prefer to mount optical telescopes away from the Earth's surface. Outline **two** advantages of placing an optical telescope in space. [2]

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(Option C continues on the following page)

(Option C continued)

14. A compound optical microscope has an objective lens with a focal length of 10.0 mm and an eyepiece lens with a focal length of 50.0 mm. An object is placed 10.6 mm from the objective lens. The final image is formed at a distance of 250 mm from the eyepiece lens.

(a) (i) Calculate the distance of the intermediate image from the objective lens. [1]

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(ii) Calculate the angular magnification of the microscope. [2]

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(b) Determine the distance between the two lenses. [2]

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(Option C continues on the following page)

(Option C continued)

15. A step-index fibre has core refractive index of 1.47 and a cladding refractive index of 1.45.

(a) (i) Calculate the critical angle at the core-cladding boundary. [1]

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(ii) The attenuation of the fibre is –5.0 dB. A signal of 12 mW is sent into the fibre. Calculate the output power from the fibre. [2]

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(b) Explain, with reference to material dispersion, the advantage of using monochromatic radiation in a fibre. [3]

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(Option C continues on the following page)

(Option C continued)

16. (a) (i) Describe how ultrasound is produced. [2]

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(ii) Distinguish between an A scan and a B scan in ultrasound medical imaging. [2]

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(Option C continues on the following page)

(Option C, question 16 continued)

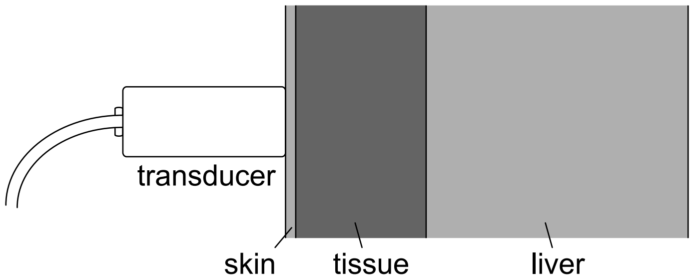
(b) When ultrasound travels from one medium to another the fraction of the incident intensity that is reflected at the boundary is called the reflection coefficient R.

The following data are available.

Reflection coefficient at skin–tissue boundary $R_{st} = 7.24 \times 10^{-3}$

Reflection coefficient at tissue–liver boundary $R_{tl} = 5.70 \times 10^{-6}$

A transducer emits ultrasound that is incident on skin. The skin transmits the ultrasound without any loss in intensity. The ultrasound is reflected from the tissue–liver boundary and is received back at the transducer.



(i) Determine the fraction of the emitted intensity of ultrasound that is detected by the transducer. [3]

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(Option C continues on the following page)

(Option C, question 16 continued)

(ii) In ultrasound scanning the distance of the liver from the skin should not exceed 250 wavelengths. Estimate the minimum frequency needed to scan a liver that is 5.0 cm from the skin–tissue boundary. The speed of sound in tissue is 1500 $m\,s^{-1}$. [2]

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(c) State **one** advantage of using ultrasound when studying the internal organs of a patient. [1]

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End of Option C

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will not be marked.

Option D — Astrophysics

17. The parallax angle of the star Vega is 0.131 arc seconds.

(a) (i) Describe what is meant by parallax angle. [1]

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(ii) Show that the distance to Vega is 25 light years. [1]

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(Option D continues on the following page)

(Option D, question 17 continued)

(b) The following information is available for the stars Vega and β Ori.

	Distance / ly	Luminosity	Temperature / K
Vega	25	$54\,L_{\odot}$	9600
β Ori	780	$40\,000\,L_{\odot}$	11 000

$L_{\odot}$ is the luminosity of our Sun.

(i) Determine whether Vega or β Ori appears brighter from Earth. [3]

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(ii) Calculate the ratio $\frac{\text{radius of } \beta \text{ Ori}}{\text{radius of Vega}}$. [3]

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(Option D continues on the following page)

(Option D, question 17 continued)

(c) (i) Vega is a main sequence star. Show that the mass of Vega is about three solar masses. [1]

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(ii) Discuss whether β Ori is a main sequence star. [2]

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(iii) Describe the most likely final stage in the evolution of Vega. [2]

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(Option D continues on the following page)

(Option D continued)

18. (a) State what is meant by the cosmic microwave background (CMB) radiation. [2]

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(b) The present temperature of the CMB is approximately 2.8 K. Calculate the peak wavelength of the CMB. [1]

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(c) The cosmic scale factor *R* of the universe at the time of the emission of the CMB was 1100 times smaller than its present value.

(i) State what is meant by the cosmic scale factor of the universe. [2]

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(ii) Explain how it may be deduced that at the time of the emission of the CMB the temperature of the universe was 1100 times higher than the present temperature. [2]

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(Option D continues on the following page)

(Option D continued)

19. (a) Suggest why

(i) a star must have a high mass in order to produce heavy elements by nuclear fusion. [2]

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(ii) elements heavier than iron can **not** be produced by nuclear fusion. [1]

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(b) Describe how neutron capture leads to the production of elements heavier than iron. [2]

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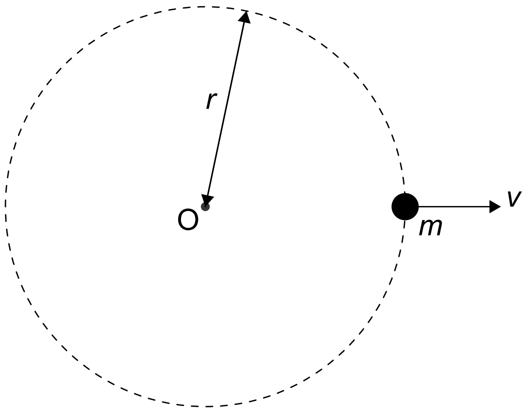
(Option D continues on the following page)

(Option D continued)

20. The universe may be considered to be filled with dust of uniform density. A particle of mass m moves with speed $v = H_0 r$ when at a distance r from a point O where H_0 is Hubble's constant. Only the mass within a sphere of radius r exerts a force on the particle.



(a) (i) Show that the point particle will just reach infinity provided that the density is

$$\frac{3{H_0}^2}{8\pi G}.$$

[2]

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(ii) Evaluate this density using $H_0 = 68\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$. [1]

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(Option D continues on the following page)

(Option D, question 20 continued)

(b) In modern cosmology the density in (a)(i) is known as the critical density. Describe the significance of this critical density for models of the universe that include dark energy. [2]

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End of Option D

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