Diploma Programme
Programme du diplôme
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Diploma Programme
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Physics
Higher level
Paper 3

7 November 2024

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 – 21

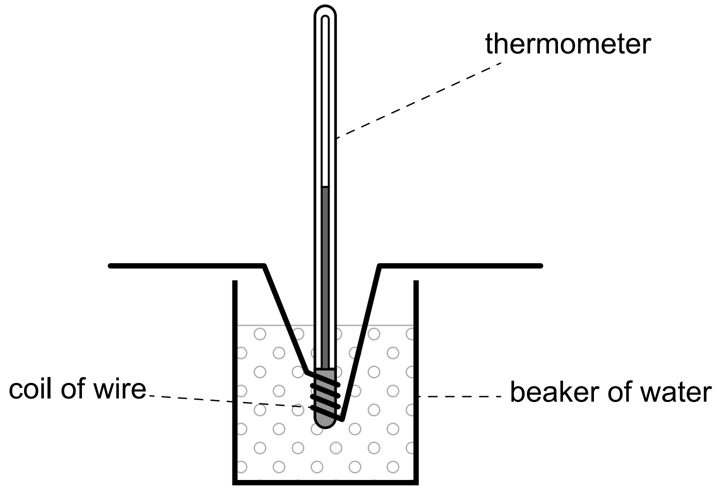
8824 – 9592

39 pages

Section A

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

1. Two students investigate the variation with temperature θ of the resistance R of a copper wire. The plastic covered copper wire is wrapped around a mercury-in-glass thermometer and immersed in a beaker of water.



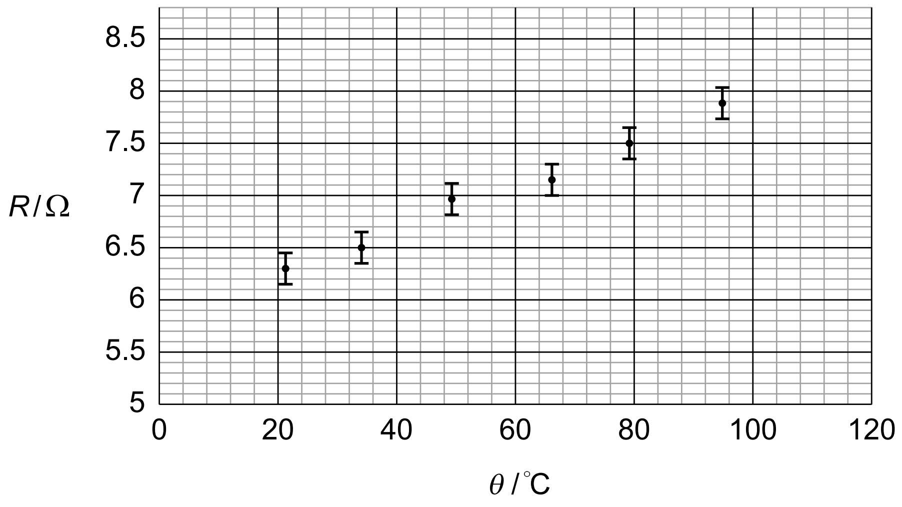
The students allow the water to cool slowly from 95 °C.

The students measure the resistance of the wire and the temperature of the water at the same instant.

(This question continues on the following page)

(Question 1 continued)

Their results are shown with error bars for R. Errors in θ can be ignored.



(a) The students suggest that R is given by $R = R_0(1 + \alpha\theta)$.

(i) Draw a line of best fit for these data that is consistent with this equation. [1]

(ii) Calculate the gradient of your best-fit line. [2]

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(iii) Deduce α. State an appropriate unit for α. [4]

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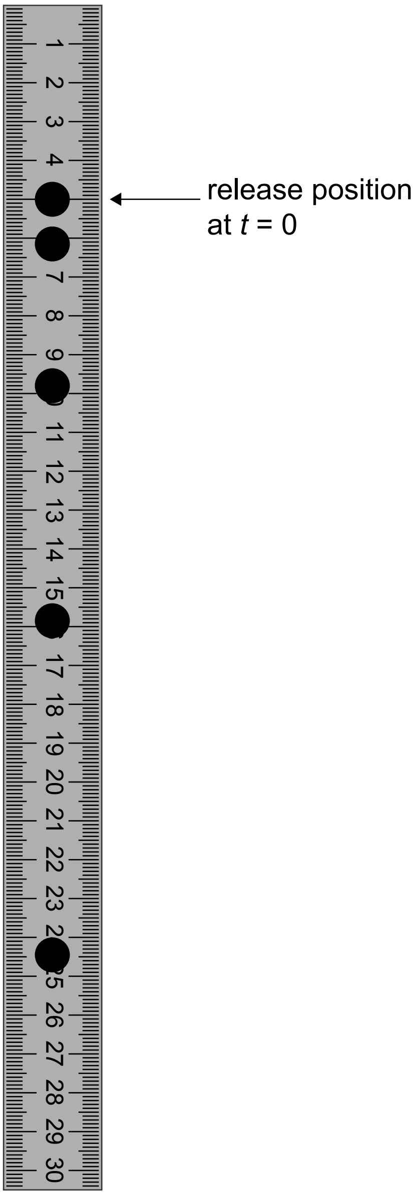
2. A small ball is released from rest at time $t = 0$ in front of a vertical ruler. A multi-flash photograph is taken of the ball at $t = 0$ and every 0.050 s from then on.



(This question continues on the following page)

(Question 2 continued)

The distance s fallen by the ball is related to the acceleration g of the ball and t by $s = \frac{1}{2}gt^2$.

(a) Determine g using the photograph. [3]

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(b) The percentage uncertainty in t is $\pm 5\%$.

Estimate the absolute uncertainty in your value of g. [3]

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(c) Suggest a suitable value for the maximum duration of the flash. [2]

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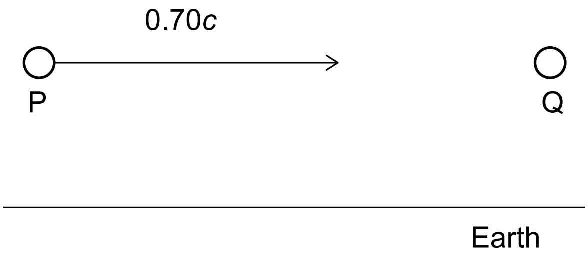
will not be marked.

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. P transmits a radio signal to Q. Relative to the Earth's surface, Q is stationary and P moves at a speed of 0.70*c* as shown.



(a) State, using Galilean relativity, the speed of the radio signal relative to Q. [1]

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(b) Determine, using relativistic velocity addition, the speed of the radio signal relative to Q. [2]

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(c) A paradigm shift in science replaced Galilean relativity with the theory of special relativity.

Explain how this paradigm shift was linked to Maxwell's discovery of a set of electromagnetic equations. [1]

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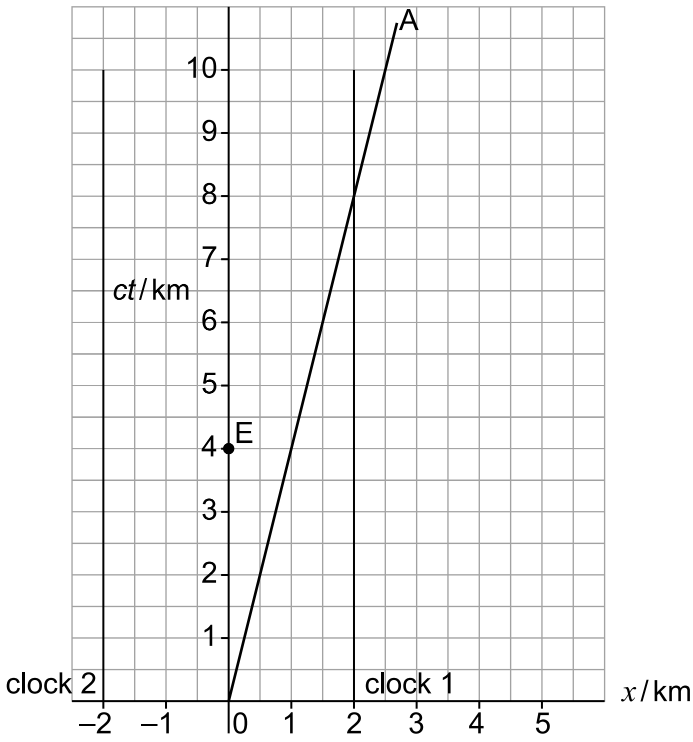
(Option A continues on the following page)

(Option A continued)

4. The spacetime diagram (x, ct) for a space station S shows the worldlines of two clocks (clock 1 and clock 2). Each clock is 2.0 km from S. The spacetime diagram also shows the worldline of spaceship A.



(Option A continues on the following page)

(Option A, question 4 continued)

(a) (i) Outline how clock 1 and clock 2 can be synchronized with a clock on S. [2]

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(ii) Determine, in terms of *c*, the speed of A in the reference frame of S. [2]

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(iii) Clock 1 and clock 2 emit separate light signals when A is at (0,0).

Identify, on the diagram, the proper time that elapses between the arrival of the light signals at A. [2]

(b) At event E, spaceship P leaves S to intercept spaceship A. The speed of P is 0.50*c* in the reference frame of S.

(i) Identify, with the letter X on the diagram, the event of P intercepting A. [1]

(ii) State, in seconds, the time of event X for clock 2. [1]

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(Option A continues on page 11)

Please **do not** write on this page.

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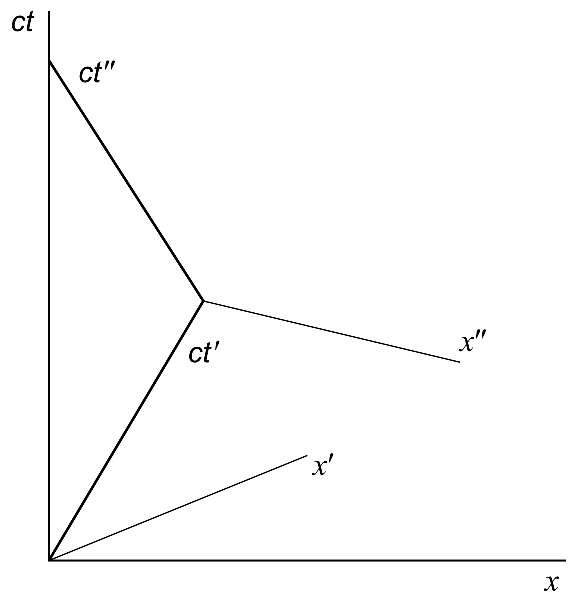
will not be marked.

(Option A, question 4 continued)

(c) Spaceship A then returns to S.

The spacetime diagram shows the rest frame of A on its outward journey (x', ct') and on its return journey (x'', ct'').



An observer in A determines, for the **reference frame of S**, the time t_1 immediately before the change of velocity of A and the time t_2 immediately after the change of velocity of A.

(i) Identify, with lines and labels on the spacetime diagram, the difference between t_1 and t_2. [2]

(ii) Explain how the difference between t_1 and t_2 arises. [1]

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(Option A continues on the following page)

(Option A continued)

5. Muons are formed in the Earth's atmosphere 2.5 km above the surface and then travel vertically downwards at a speed of $0.975c$. The mean lifetime of a muon is 2.2 μs when measured in a frame in which the muon is at rest.

(a) Calculate the mean lifetime of the muon for the reference frame of the Earth. [2]

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(b) Muons are detected at the Earth's surface.

Explain, with supporting calculations, why this is evidence for time dilation. [3]

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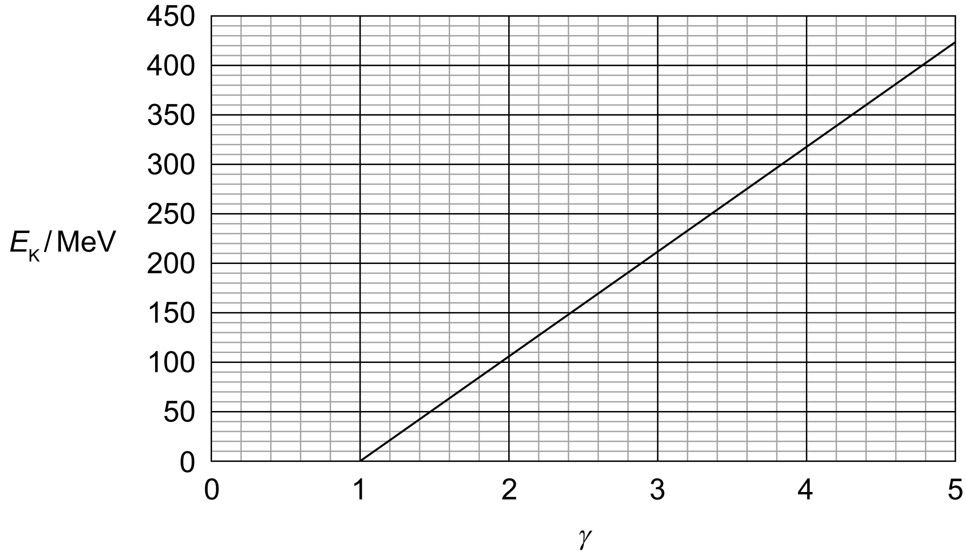
(Option A continues on the following page)

(Option A continued)

6. The graph shows the variation of kinetic energy E_K with γ (gamma factor) for a muon.



(a) Calculate the rest energy of the muon. [2]

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(b) The muon has the same charge as an electron. Deduce the potential difference required to accelerate a muon from rest to a speed of 0.96*c*. [2]

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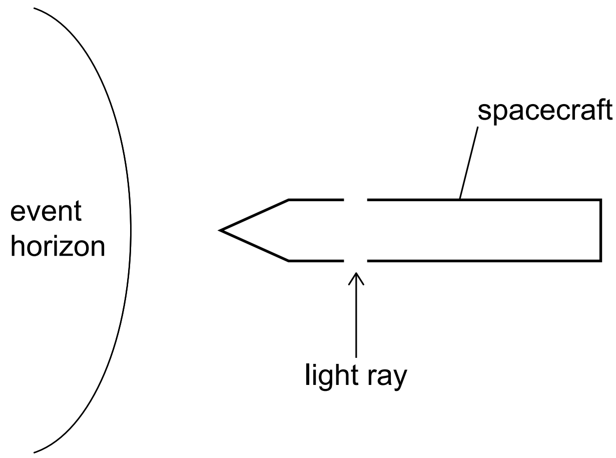
(Option A continues on the following page)

(Option A continued)

7. A distant observer observes a spacecraft that is falling freely towards a black hole.

According to an observer in the spacecraft, a light ray enters an observation window of the spacecraft and leaves through a second window directly opposite the first.



(a) Explain the difference between the path of the light ray as described by the distant observer and the path of the light ray as described by the observer in the spacecraft. [3]

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(Option A continues on the following page)

(Option A, question 7 continued)

(b) The event horizon is 300 km from the centre of the black hole.

When the spacecraft is at 100 km from the event horizon of the black hole it transmits a radio signal to the distant observer. The duration of the radio message according to the observer on the spacecraft is 7.5 μs.

(i) Calculate the duration of the radio message as received by the distant observer. [2]

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(ii) Calculate the mass of the black hole. [1]

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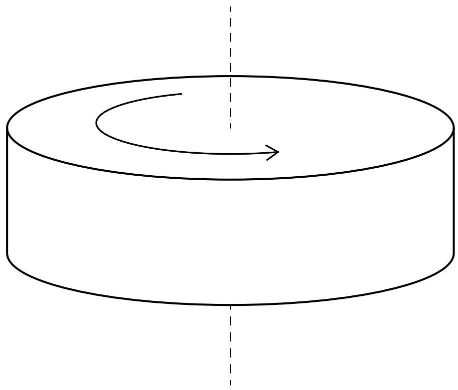
End of Option A

Option B — Engineering physics

8. A flywheel is a rotating cylinder used to store rotational kinetic energy. Energy can be transferred from the flywheel as it slows down.



A flywheel used to store energy has a moment of inertia of 0.072 $kg\,m^2$ and a maximum angular speed of 8400 $rad\,s^{-1}$.

(Option B continues on the following page)

(Option B, question 8 continued)

(a) The rotational speed of the flywheel is reduced uniformly from the maximum speed to 3600 rad s^{-1} in a time of 9.6 s.

(i) Show that an average power of about 200 kW is transferred from the flywheel as its speed is reduced. [2]

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(ii) Calculate the torque acting on the flywheel as it decelerates. [2]

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(iii) Calculate the number of revolutions that the flywheel makes as it slows down. [2]

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(b) An engineer changes the flywheel design to increase the maximum energy that it can store.

Identify **two** factors that the engineer can change to do this. [2]

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(Option B continues on page 19)

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will not be marked.

(Option B continued)

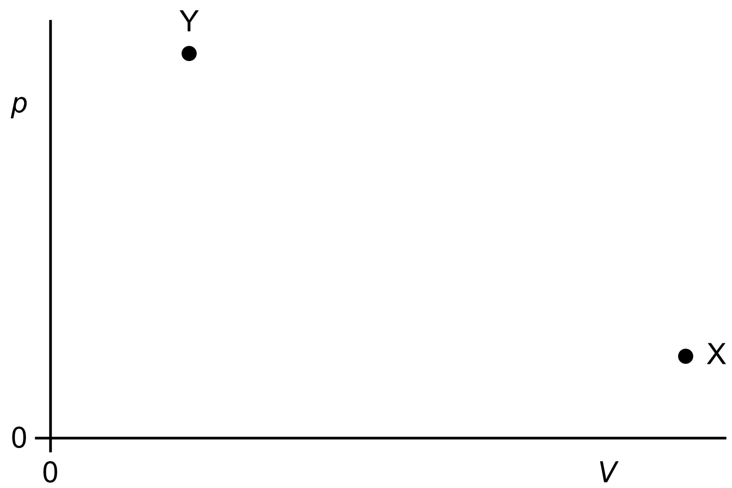
9. A fixed mass of an ideal gas is taken through a cycle that consists of three processes:

$X \rightarrow Y$ Isothermal compression from a pressure of 0.10 MPa and volume of 1.20×10^{-3} m^3 to a pressure of 0.48 MPa

$Y \rightarrow Z$ Isobaric expansion

$Z \rightarrow X$ Adiabatic expansion to the initial state

(a) Draw, on the axes, the *pV* diagram for this cycle. X and Y are plotted for you. Numbers are not required on the axes. [2]



(b) Show that the volume of the gas at Y is 0.25×10^{-3} m^3. [1]

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(Option B continues on the following page)

(Option B, question 9 continued)

(c) An algebraic statement of the first law of thermodynamics is $Q = \Delta U + W$.

Data for the cycle are provided in the table.

Process	***Q* / J**	**Δ*U* / J**	***W* / J**
X → Y			−188
Y → Z	+262		+105
Z → X			+157
whole cycle			+74

(i) Complete the table. Use the answer box below for your calculations. [3]

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(ii) Determine the volume of the gas at Z. [2]

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(iii) Determine the efficiency of this cycle. [2]

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(Option B continues on the following page)

(Option B, question 9 continued)

(d) Outline why this theoretical cycle is unsuitable for use in a practical heat engine. [2]

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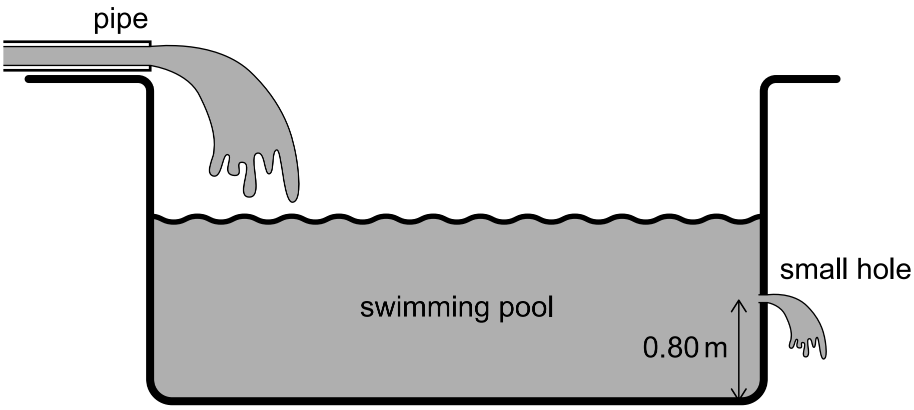
(Option B continues on the following page)

(Option B continued)

10. A swimming pool consists of a large tank above ground that is being filled with water. The water flows into the tank through a pipe of radius 0.13 m at a flow speed of 66 mm s^{-1}.

diagram not to scale



Density of water = 1000 kg m^{-3}
Viscosity of water = 1.1 × 10^{-3} Pa s

(a) Identify whether the flow of the water in the pipe is likely to be turbulent. [1]

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(b) There is a small hole in the side of the tank through which water escapes.

The small hole is 0.80 m above the bottom of the tank and the radius of the small hole is 19 mm. The depth of water *d* does not change once the flow rate **into** the tank is equal to the flow rate **out of** the tank.

Determine this constant value of *d*. [3]

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(Option B continues on the following page)

(Option B, question 10 continued)

(c) A block of wood floats on the surface of the water.

Outline, with reference to pressure, the origin of the buoyancy force on the block. [2]

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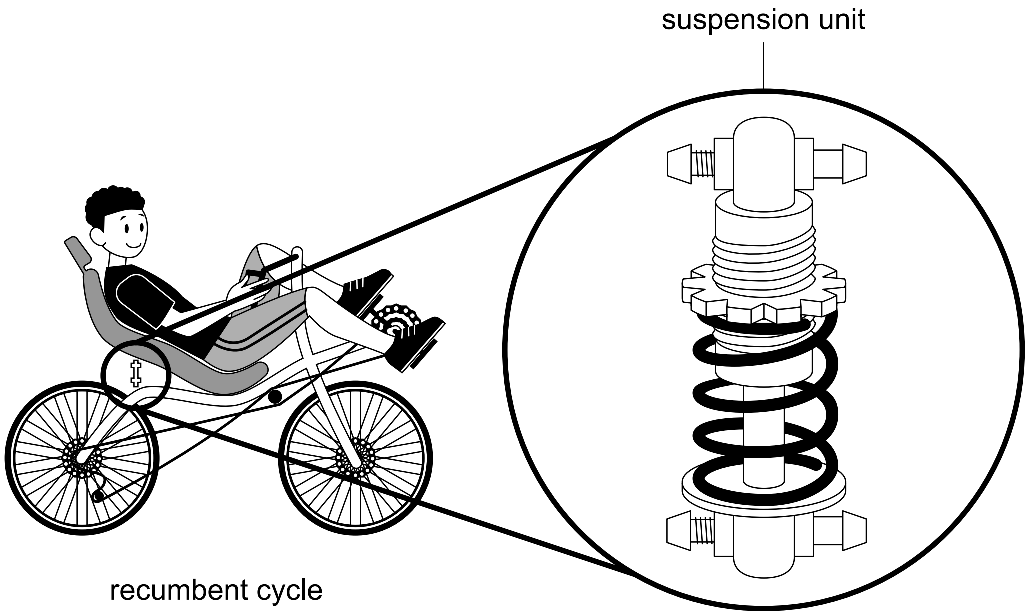
(Option B continues on the following page)

(Option B continued)

11. A person rides a recumbent bicycle that has a suspension unit mounted between the saddle and the bicycle frame. The suspension unit supports the mass of the person and consists of a spring with a damping mechanism.

The natural frequency of vibration of the suspension unit is 2.6 Hz.



The suspension unit is damaged so that the spring is undamped.

The bicycle travels over bumpy ground with bumps separated by equal distances of 1.2 m.

(a) Explain why the ride is uncomfortable when the speed of the bicycle is $3.0\,m\,s^{-1}$. [2]

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(Option B continues on the following page)

(Option B, question 11 continued)

(b) The suspension unit is repaired so that the spring is damped.

Describe any changes that the person will notice when riding over the same bumpy ground. [2]

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End of Option B

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will not be marked.

Option C — Imaging

12. A real image, four times larger than the object, is formed 0.40 m from a converging lens.

(a) Calculate the focal length of the lens. [3]

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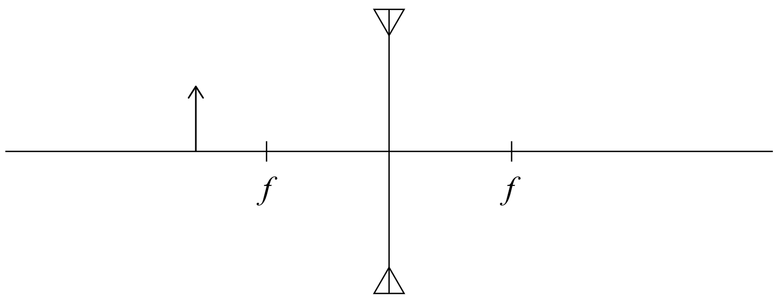
(b) The converging lens is replaced by a diverging lens of focal length f. The position of the object is shown.



Determine, using a ray diagram, the nature of the image formed. [2]

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(Option C continues on the following page)

(Option C continued)

13. (a) (i) Identify the optical components in an astronomical reflecting telescope with Newtonian mounting. [2]

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(ii) Explain **one** advantage that an astronomical reflecting telescope with a Cassegrain mounting has over one with a Newtonian mounting. [1]

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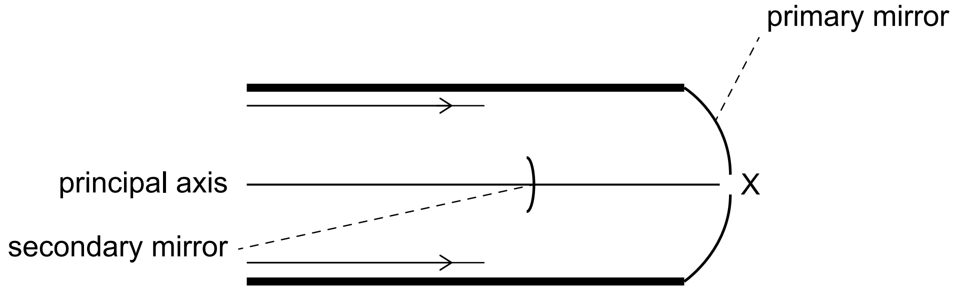
(Option C continues on the following page)

(Option C, question 13 continued)

(b) In a reflecting telescope with a Cassegrain mounting, the primary mirror has a focal length of 8.0 m. The telescope is used to view a feature on the Moon that subtends an angle of 2.5 mrad at the axis of the primary mirror.



(i) Calculate the height of the image formed by the primary mirror. [1]

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(ii) The initial paths of two rays parallel to the principal axis are shown on the diagram. Show, by completing the paths of these rays, the formation of the final image at X. [2]

(iii) The secondary mirror is 4.5 m from X. Calculate the focal length of the secondary mirror. [2]

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(Option C continues on the following page)

(Option C continued)

14. Light propagates along an optic fibre that has a core of refractive index 1.59 and a cladding of refractive index 1.48.

(a) Show that the critical angle at the core-cladding boundary is approximately 70°. [2]

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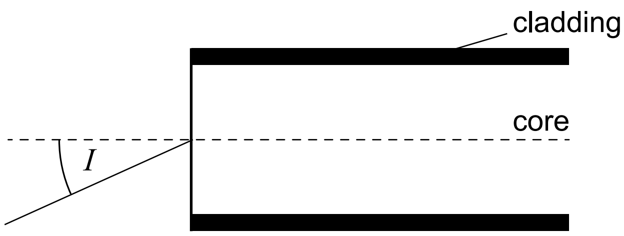
(b) A ray enters the optic fibre from the air through a core surface that is at 90° to the axis of the fibre.



(i) Determine the largest angle of incidence I that this ray can have in the air for total internal reflection to occur at the core-cladding boundary. [2]

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(ii) Describe what happens to rays of light with angles of incidence greater than I. [1]

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(Option C continues on the following page)

(Option C, question 14 continued)

(c) The attenuation per unit length in the core material is $5.5\,\text{dB}\,\text{km}^{-1}$.

Estimate the length of the optic fibre that will reduce the brightness of light by a factor of 10^6. [2]

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(Option C continues on the following page)

(Option C continued)

15. (a) Distinguish between mass attenuation coefficient and linear attenuation coefficient as used in X-ray imaging. [2]

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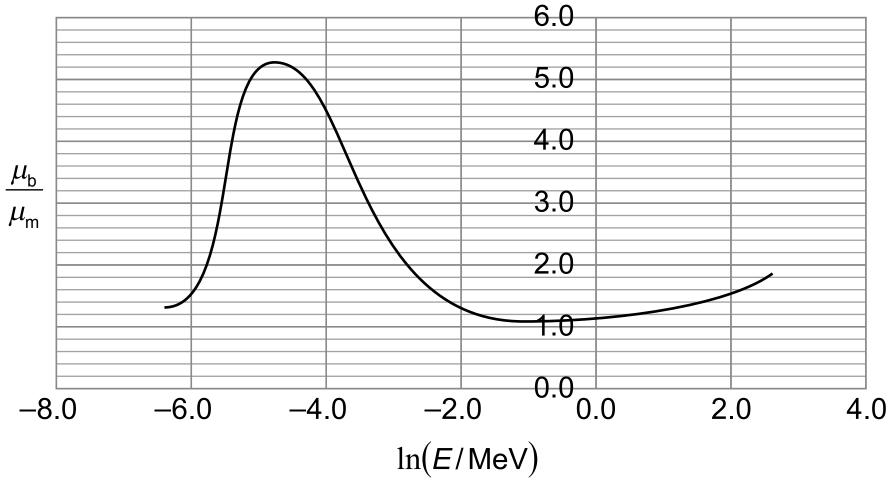
(Option C continues on the following page)

(Option C, question 15 continued)

(b) Monochromatic X-radiation of photon energy E is used to image a bone fracture in a human leg. The mass attenuation coefficient for the bone is μ_b and the mass attenuation coefficient for the muscle around the bone is μ_m. The graph shows the variation of $\frac{\mu_b}{\mu_m}$ with $\ln(E/\text{MeV})$.



Justify, in eV, the photon energy that is most suitable for imaging the bone fracture. [4]

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(Option C continues on the following page)

(Option C continued)

16. In a nuclear magnetic resonance (NMR) scanner, a patient is placed in a magnetic field formed by combining gradient and uniform fields.

(a) Outline why magnetic fields are used. [1]

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(b) Outline how the gradient magnetic field allows the location of a signal from the patient to be determined. [3]

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End of Option C

Option D — Astrophysics

17. (a) Outline the differences between open stellar clusters and globular stellar clusters. [2]

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(b) Discuss how Cepheid variable stars are used for distance determinations in astronomy. [3]

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(c) Galactic dust absorbs light.

Predict the effect that galactic dust has on the estimate of the distance to a Cepheid variable star. [2]

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(Option D continues on the following page)

Turn over

(Option D continued)

18. Data for the main-sequence star 10 Lacertae are provided. $T_{\odot}$ and $L_{\odot}$ refer to the temperature of the Sun and to the luminosity of the Sun.

surface temperature of 10 Lacertae $= 6.3\,T_{\odot}$

luminosity of 10 Lacertae $= 100\,000\,L_{\odot}$

(a) Calculate $\dfrac{\text{radius of 10 Lacertae}}{\text{radius of the Sun}}$. [3]

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(b) Show that the mass of 10 Lacertae is about 30 times the mass of the Sun. [2]

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(c) Outline, with reference to its mass, the likely final state of 10 Lacertae. [2]

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(Option D continues on the following page)

(Option D continued)

19. The galaxy NGC 6251 is 350 Mly from Earth and has a redshift of 0.025.

(a) Show that the NGC 6251 data lead to an estimate for the Hubble constant of about $70\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$. [3]

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(b) (i) Estimate, using your answer to (a), the age of the universe in seconds. [2]

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(ii) State the assumption you made in your estimate for (b)(i). [1]

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(Option D continues on the following page)

(Option D continued)

20. The Jeans mass M_j of an interstellar gas cloud is equal to $\frac{CRT}{m}$ where:

R is the radius of the gas cloud

T is the temperature of the gas cloud

m is the mass of the particles in the cloud

C is a constant that has the value $6.2 \times 10^{-13}\,\text{kg}^2\,\text{m}^{-1}\,\text{K}^{-1}$.

(a) Outline the significance of M_j. [2]

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(b) A spherical gas cloud of radius $7 \times 10^{15}\,\text{m}$ contains particles of mass $3.3 \times 10^{-27}\,\text{kg}$ at a density of $5.0 \times 10^{-19}\,\text{kg}\,\text{m}^{-3}$. The mean temperature of the cloud is 10 K.

Determine the stability of this cloud. [4]

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(Option D continues on the following page)

(Option D continued)

21. (a) Explain why the cosmological principle suggests that there can be no boundary to the universe. [2]

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(b) The Planck Space Observatory revealed temperature fluctuations in the Cosmic Microwave Background (CMB) radiation. Outline **one** consequence of these fluctuations. [2]

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End of Option D

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