Diploma Programme
Programme du diplôme
Programa del Diploma

Physics
Higher level
Paper 3

Wednesday 31 October 2018 (morning)

1 hour 15 minutes

Candidate session number

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

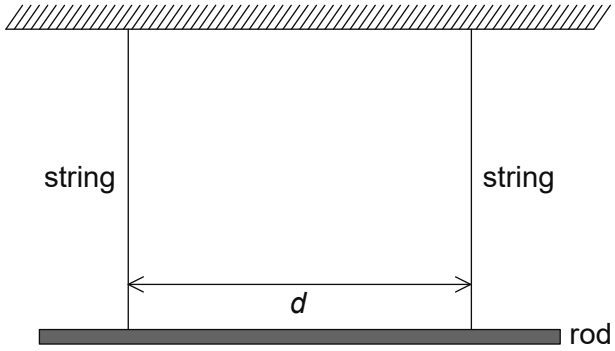
Section B	Questions
Answer all of the questions from one of the options.	
Option A — Relativity	3 – 7
Option B — Engineering physics	8 – 11
Option C — Imaging	12 – 16
Option D — Astrophysics	17 – 21

8818 – 6503

Section A

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

1. In an investigation to measure the acceleration of free fall a rod is suspended horizontally by two vertical strings of equal length. The strings are a distance *d* apart.



When the rod is displaced by a small angle and then released, simple harmonic oscillations take place in a horizontal plane.

The theoretical prediction for the period of oscillation T is given by the following equation

$$T = \frac{c}{d\sqrt{g}}$$

where c is a known numerical constant.

(a) State the unit of c. [1]

. . . . . .

(b) A student records the time for 20 oscillations of the rod. Explain how this procedure leads to a more accurate measurement of the time for **one** oscillation T. [2]

. . . . . .

. . . . . .

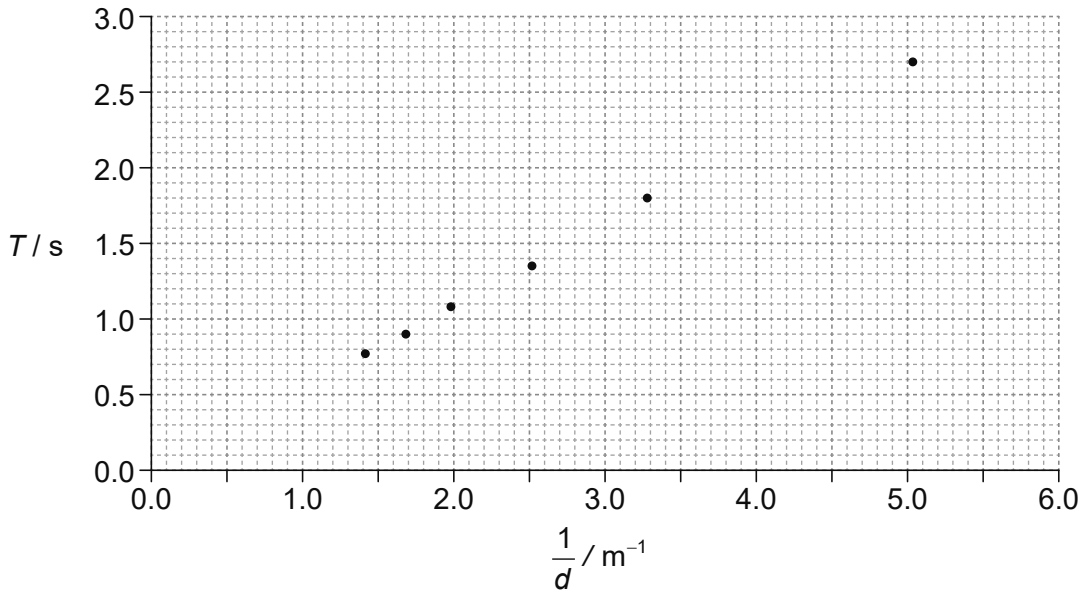
. . . . . .

. . . . . .

(This question continues on the following page)

(Question 1 continued)

(c) In one experiment d was varied. The graph shows the plotted values of T against $\frac{1}{d}$. Error bars are negligibly small.



(i) Draw the line of best fit for these data. [1]

(ii) Suggest whether the data are consistent with the theoretical prediction. [2]

. . . . . .

. . . . . .

. . . . . .

. . . . . .

(This question continues on the following page)

(Question 1 continued)

(d) The numerical value of the constant c in SI units is 1.67. Determine g, using the graph. [4]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

2. In an experiment to measure the specific latent heat of vaporization of water L_v, a student uses an electric heater to boil water. A mass m of water vaporizes during time t. L_v may be calculated using the relation

$$L_v = \frac{VIt}{m}$$

where V is the voltage applied to the heater and I the current through it.

(a) Outline why, during the experiment, V and I should be kept constant. [1]

. . . . . .

. . . . . .

(b) Outline whether the value of L_v calculated in this experiment is expected to be larger or smaller than the actual value. [2]

. . . . . .

. . . . . .

. . . . . .

. . . . . .

(c) A student suggests that to get a more accurate value of L_v the experiment should be performed twice using different heating rates. With voltage and current V_1, I_1 the mass of water that vaporized in time t is m_1. With voltage and current V_2, I_2 the mass of water that vaporized in time t is m_2. The student now uses the expression

$$L_v = \frac{(V_1 I_1 - V_2 I_2)t}{m_1 - m_2}$$

to calculate L_v. Suggest, by reference to heat losses, why this is an improvement. [2]

. . . . . .

. . . . . .

. . . . . .

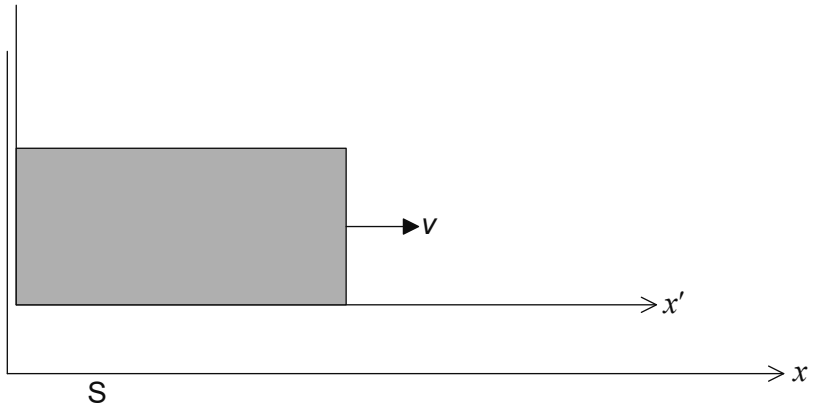
. . . . . .

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. The diagram shows the axes for two inertial reference frames. Frame S represents the ground and frame S′ is a box that moves to the right relative to S with speed *v*.



(a) State what is meant by a reference frame. [1]

. . . . . .

. . . . . .

(Option A continues on the following page)

(Option A, question 3 continued)

(b) When the origins of the two frames coincide all clocks show zero. At that instant a beam of light of speed c is emitted from the left wall of the box towards the right wall. The box has proper length L. Consider the event E = light arrives at the right wall of the box.

Using **Galilean** relativity,

(i) explain why the time coordinate of E in frame S is $t = \frac{L}{c}$. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

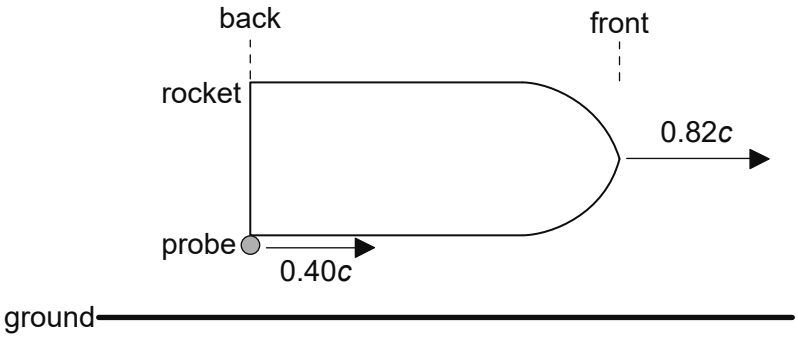
(ii) hence show that the space coordinate of E in frame S is $x = L + \frac{vL}{c}$. [1]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

(Option A continues on the following page)

(Option A continued)

4. A rocket of proper length 120 m moves to the right with speed 0.82*c* relative to the ground.



A probe is released from the back of the rocket at speed 0.40*c* relative to the rocket.

(a) Calculate the speed of the probe relative to the ground. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

(Option A continues on the following page)

(Option A, question 4 continued)

(b) Determine the time it takes the probe to reach the front of the rocket according to an observer

(i) at rest in the rocket. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

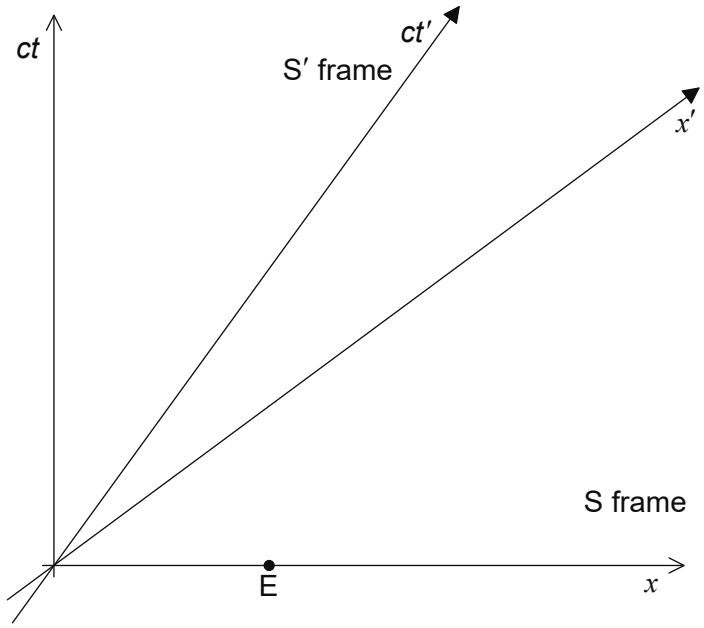
(ii) at rest on the ground. [3]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

(Option A continues on the following page)

(Option A continued)

5. The spacetime diagram shows the axes of an inertial reference frame S and the axes of a second inertial reference frame S′ that moves relative to S with speed 0.745*c*. When clocks in both frames show zero the origins of the two frames coincide.



(a) Event E has coordinates $x = 1$ m and $ct = 0$ in frame S. Show that in frame S′ the space coordinate and time coordinate of event E are

(i) $x' = 1.5$ m. [2]

. . . . . .
. . . . . .
. . . . . .

(ii) $ct' = -1.1$ m. [1]

. . . . . .
. . . . . .
. . . . . .

(Option A continues on the following page)

(Option A, question 5 continued)

(b) Label, on the diagram,

(i) the space coordinate of event E in the S′ frame. Label this event with the letter P. [1]

(ii) the event that has coordinates $x' = 1.0$ m and $ct' = 0$. Label this event with the letter Q. [1]

(c) A rod at rest in frame S has proper length 1.0 m. At $t = 0$ the left-hand end of the rod is at $x = 0$ and the right-hand end is at $x = 1.0$ m.

Using the spacetime diagram,

(i) outline without calculation, why observers in frame S′ measure the length of the rod to be less than 1.0 m. [3]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

(ii) estimate, in m, the length of this rod in the S′ frame. [1]

. . . . . .
. . . . . .

(Option A continues on the following page)

(Option A continued)

6. An electron with total energy 1.50 MeV collides with a positron at rest. As a result two photons are produced. One photon moves in the same direction as the electron and the other in the opposite direction.

(a) Show that the momentum of the electron is 1.41 MeV c^{-1}. [1]

. . . . . .
. . . . . .
. . . . . .

(b) The momenta of the photons produced have magnitudes p_1 and p_2. A student writes the following correct equations.

$$p_1 - p_2 = 1.41 \text{ MeV } c^{-1}$$
$$p_1 + p_2 = 2.01 \text{ MeV } c^{-1}$$

(i) Explain the origin of each equation. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

(ii) Calculate, in MeV c^{-1}, p_1 and p_2. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

(Option A continues on the following page)

(Option A continued)

7. A probe launched from a spacecraft moves towards the event horizon of a black hole.

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

. . . . . .

. . . . . .

(ii) The mass of the black hole is 4.0×10^{36} kg. Calculate the Schwarzschild radius of the black hole. [1]

. . . . . .

. . . . . .

(b) The probe is stationary above the event horizon of the black hole in (a). The probe sends a radio pulse every 1.0 seconds (as measured by clocks on the probe). The spacecraft receives the pulses every 2.0 seconds (as measured by clocks on the spacecraft). Determine the distance of the probe from the centre of the black hole. [3]

. . . . . .

. . . . . .

. . . . . .

. . . . . .

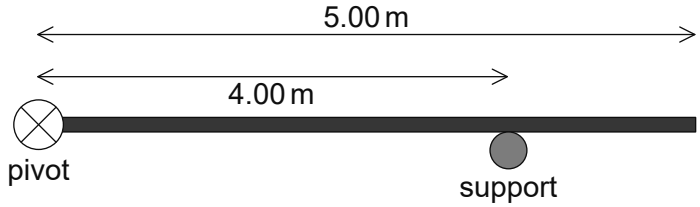
. . . . . .

. . . . . .

End of Option A

Option B — Engineering physics

8. A uniform rod of weight 36.0 N and length 5.00 m rests horizontally. The rod is pivoted at its left-hand end and is supported at a distance of 4.00 m from the frictionless pivot.



(a) Calculate the force the support exerts on the rod. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

(b) The support is suddenly removed and the rod begins to rotate clockwise about the pivot point. The moment of inertia of the rod about the pivot point is 30.6 kg m^2.

(i) Calculate, in rad s^{-2}, the initial angular acceleration α of the rod. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

(ii) After time *t* the rod makes an angle θ with the horizontal. Outline why the equation $\theta = \frac{1}{2}\alpha t^2$ **cannot** be used to find the time it takes θ to become $\frac{\pi}{2}$ (that is for the rod to become vertical for the first time). [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

(Option B continues on the following page)

(Option B, question 8 continued)

(c) At the instant the rod becomes vertical

(i) show that the angular speed is $\omega = 2.43\ \text{rad s}^{-1}$. [3]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

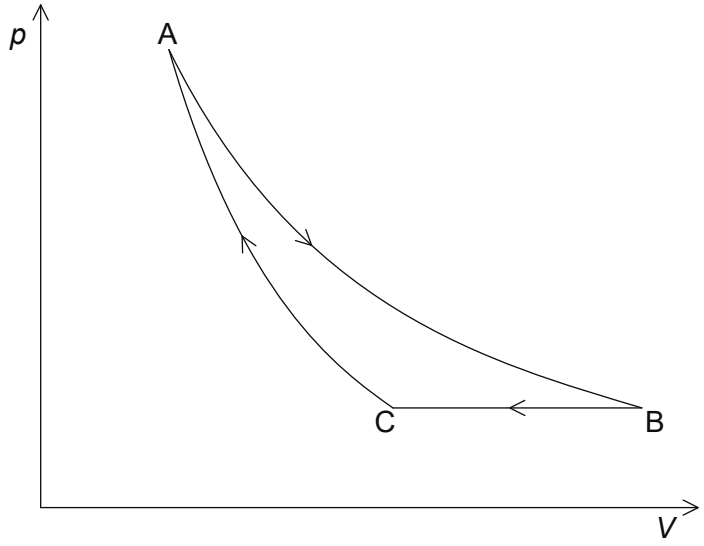
(ii) calculate the angular momentum of the rod. [1]

. . . . . .
. . . . . .
. . . . . .

(Option B continues on the following page)

(Option B continued)

9. The *pV* diagram of a heat engine using an ideal gas consists of an isothermal expansion A → B, an isobaric compression B → C and an adiabatic compression C → A.



The following data are available:

Temperature at A	$= 385\,\text{K}$
Pressure at A	$= 2.80 \times 10^{6}\,\text{Pa}$
Volume at A	$= 1.00 \times 10^{-4}\,\text{m}^3$
Volume at B	$= 2.80 \times 10^{-4}\,\text{m}^3$
Volume at C	$= 1.85 \times 10^{-4}\,\text{m}^3$

(Option B continues on the following page)

(Option B, question 9 continued)

(a) Show that at C the

(i) pressure is 1.00×10^6 Pa. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

(ii) temperature is 254 K. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

(b) Show that the thermal energy transferred from the gas during the change B → C is 238 J. [3]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

(Option B continues page 19)

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

Answers written on this page
will not be marked.

(Option B, question 9 continued)

(c) (i) The work done by the gas from A → B is 288 J. Calculate the efficiency of the cycle. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

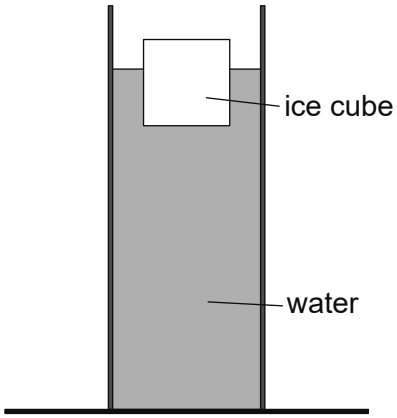
(ii) State, without calculation, during which change (A → B, B → C or C → A) the entropy of the gas decreases. [1]

. . . . . .
. . . . . .
. . . . . .

(Option B continues on the following page)

(Option B continued)

10. (a) An ice cube floats in water that is contained in a tube.



The ice cube melts.

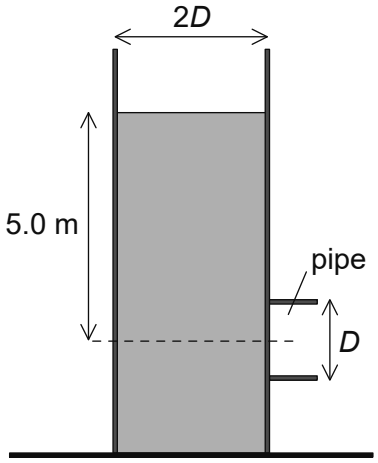
Suggest what happens to the level of the water in the tube. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

(Option B continues on the following page)

(Option B, question 10 continued)

(b) A horizontal pipe is inserted into the cylindrical tube so that its centre is at a depth of 5.0 m from the surface of the water. The diameter D of the pipe is half that of the tube.



When the pipe is opened, water exits the pipe with speed u and the surface of the water in the tube moves downwards with speed v.

(i) Outline why $u = 4v$. [2]

. . . . . .
. . . . . .

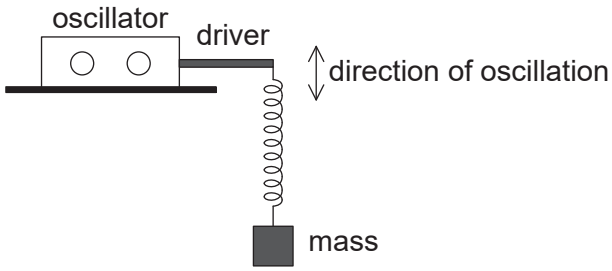
(ii) The density of water is 1000 kg m^{-3}. Calculate u. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

(Option B continues on the following page)

(Option B continued)

11. A mass is attached to a vertical spring. The other end of the spring is attached to the driver of an oscillator.



The mass is performing very lightly damped harmonic oscillations. The frequency of the driver is **higher** than the natural frequency of the system. At one instant the driver is moving downwards.

(a) State and explain the direction of motion of the mass at this instant. [2]

. . . . . .

. . . . . .

. . . . . .

. . . . . .

(b) The oscillator is switched off. The system has a *Q* factor of 22. The initial amplitude is 10 cm. Determine the amplitude after **one** complete period of oscillation. [2]

. . . . . .

. . . . . .

. . . . . .

. . . . . .

. . . . . .

. . . . . .

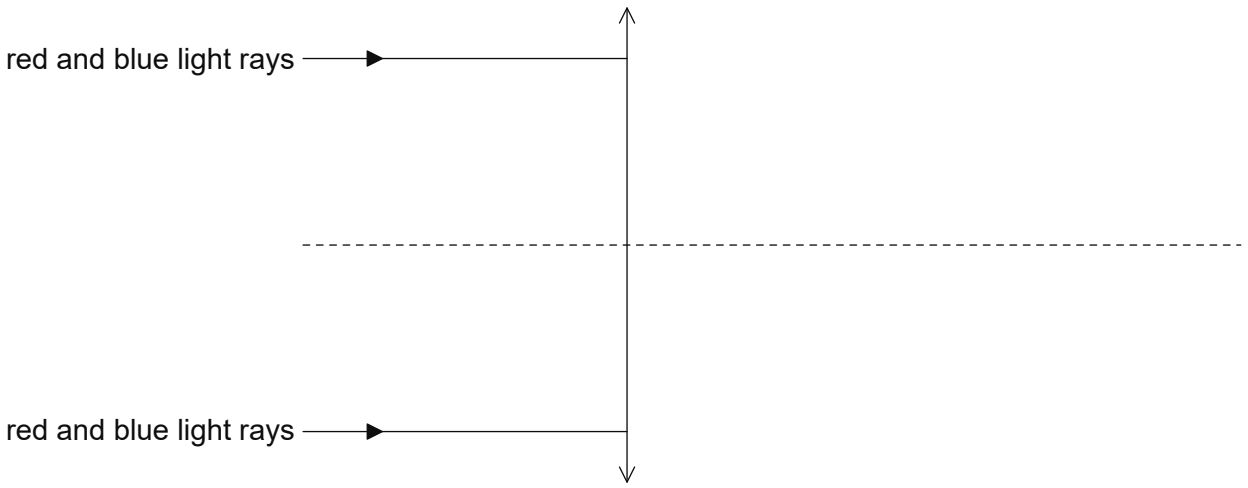
. . . . . .

. . . . . .

End of Option B

Option C — Imaging

12. The refractive index of glass decreases with increasing wavelength. The diagram shows rays of light incident on a converging lens made of glass. The light is a mixture of red and blue light.



(a) On the diagram, draw lines to show the rays after they have refracted through the lens. Label the refracted red rays with the letter R and the refracted blue rays with the letter B. [3]

(b) (i) Suggest how the refracted rays in (a) are modified when the converging lens is replaced by a diverging lens. [1]

. . . . . .

. . . . . .

(ii) Hence state how the defect of the converging lens in (a) may be corrected. [1]

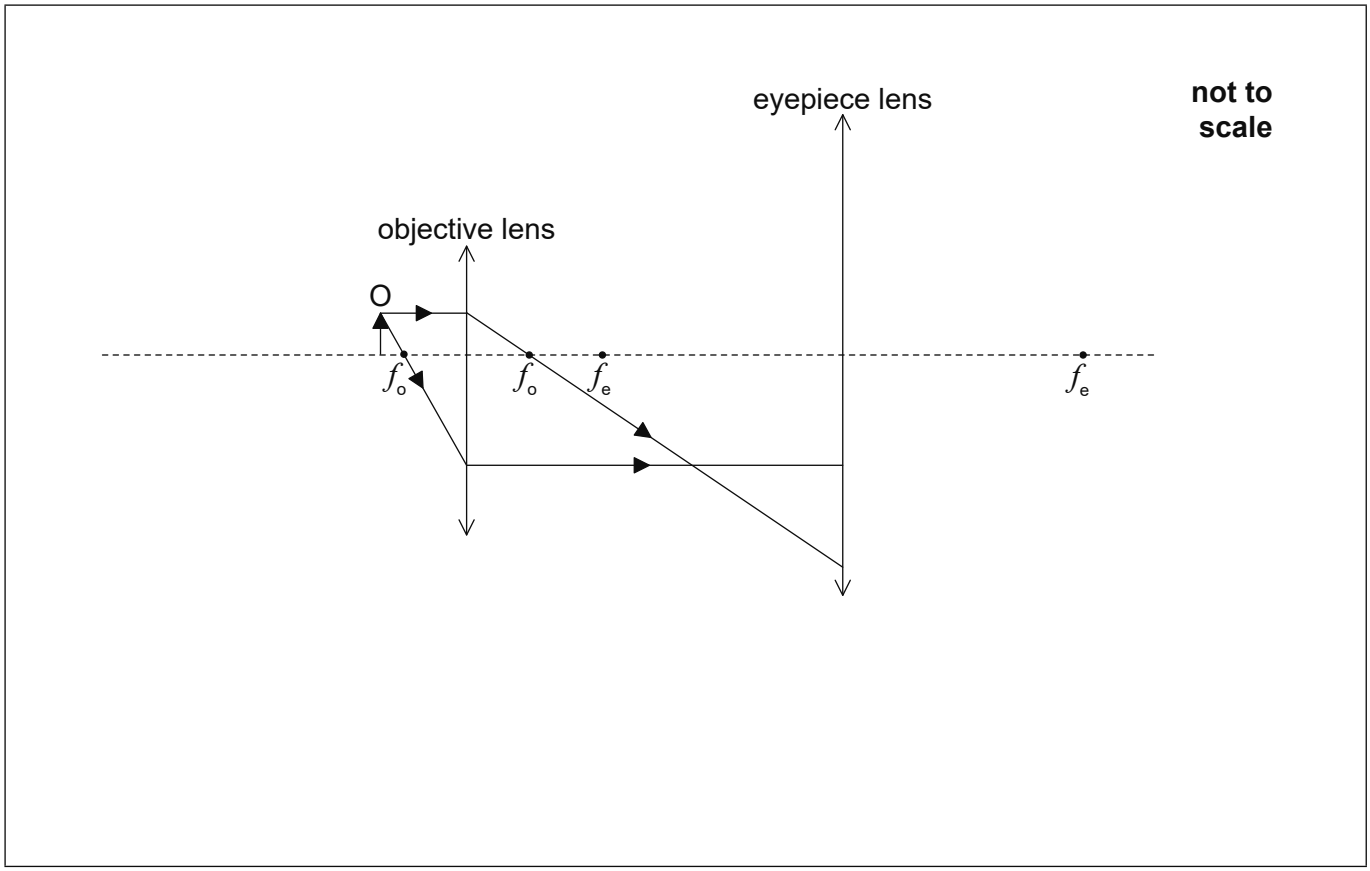
. . . . . .

. . . . . .

(Option C continues on the following page)

(Option C continued)

13. The diagram shows two light rays that form an intermediate image by the objective lens of an optical compound microscope. These rays are incident on the eyepiece lens. The focal points of the two lenses are marked.



(a) Draw rays on the diagram to show the formation of the final image. [2]

(Option C continues on the following page)

(Option C, question 13 continued)

(b) The object O is placed at a distance of 24.0 mm from the objective lens and the final image is formed at a distance 240 mm from the eyepiece lens. The focal length of the objective lens is 20.0 mm and that of the eyepiece lens is 60.0 mm. The near point of the observer is at a distance of 240 mm from the eyepiece lens.

(i) Calculate the distance between the lenses. [3]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

(ii) Determine the magnification of the microscope. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

(Option C continues on the following page)

(Option C continued)

14. (a) An optic fibre consists of a glass core of refractive index 1.52 surrounded by cladding of refractive index n. The critical angle at the glass–cladding boundary is 84°.

(i) Calculate n. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

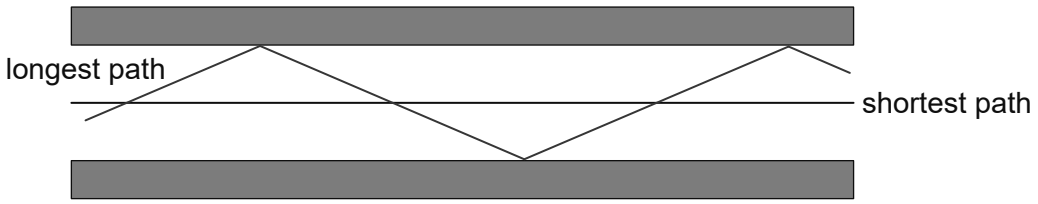
(ii) The refractive indices of the glass and cladding are only slightly different. Suggest why this is desirable. [1]

. . . . . .
. . . . . .
. . . . . .

(Option C continues on the following page)

(Option C, question 14 continued)

(b) The diagram shows the longest and shortest paths that a ray can follow inside the fibre.



not to scale

For the longest path the rays are incident at the core–cladding boundary at an angle just slightly greater than the critical angle. The optic fibre has a length of 12 km.

(i) Show that the longest path is 66 m longer than the shortest path. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

(ii) Determine the time delay between the arrival of signals created by the extra distance in (b)(i). [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

(iii) Suggest whether this fibre could be used to transmit information at a frequency of 100 MHz. [1]

. . . . . .
. . . . . .
. . . . . .

(Option C continues on page 29)

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

Answers written on this page
will not be marked.

(Option C continued)

15. In nuclear magnetic resonance imaging (NMR) a patient is exposed to a strong external magnetic field so that the spin of the protons in the body align parallel or antiparallel to the magnetic field. A pulse of a radio frequency (RF) electromagnetic wave is then directed at the patient.

(a) Describe the effect of the RF signal on the protons in the body. [1]

. . . . . .
. . . . . .

(b) Outline the measurement that needs to be made after the RF signal is turned off. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

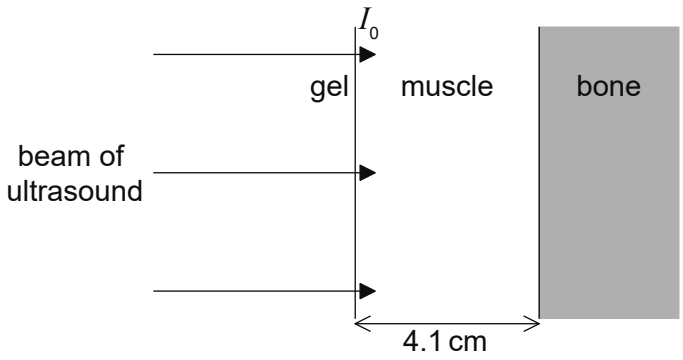
(c) Describe how the measurement in (b) provides diagnostic information for the doctor. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

(Option C continues on the following page)

(Option C continued)

16. A beam of ultrasound of intensity I_0 enters a layer of muscle of thickness 4.1 cm.



The fraction of the intensity that is reflected at a boundary is

$$\left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2$$

where Z_1 and Z_2 are the acoustic impedances of the two media at the boundary. After travelling a distance x in a medium the intensity of ultrasound is reduced by a factor $e^{-\mu x}$ where μ is the absorption coefficient.

The following data are available.

Acoustic impedance of muscle $= 1.7 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$
Acoustic impedance of bone $= 6.3 \times 10^6 \text{ kg m}^{-2} \text{ s}^{-1}$
Absorption coefficient of muscle $= 23 \text{ m}^{-1}$

(Option C continues on the following page)

(Option C, question 16 continued)

Determine, in terms of I_0, the intensity of ultrasound that

(a) is incident on the muscle–bone boundary. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

(b) is reflected at the muscle–bone boundary. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

(c) returns to the muscle–gel boundary. [1]

. . . . . .
. . . . . .

End of Option C

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

Answers written on this page
will not be marked.

Option D — Astrophysics

17. A distinctive feature of the constellation Orion is the Trapezium, an open cluster of stars within Orion.

(a) Distinguish between a constellation and an open cluster. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

(b) Mintaka is one of the stars in Orion.

(i) The parallax angle of Mintaka measured from Earth is 3.64×10^{-3} arc-second. Calculate, in parsec, the approximate distance of Mintaka from Earth. [1]

. . . . . .
. . . . . .

(ii) State why there is a maximum distance that astronomers can measure using stellar parallax. [1]

. . . . . .
. . . . . .

(c) The Great Nebula is located in Orion. Describe, using the Jeans criterion, the necessary condition for a nebula to form a star. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

(Option D continues on the following page)

(Option D continued)

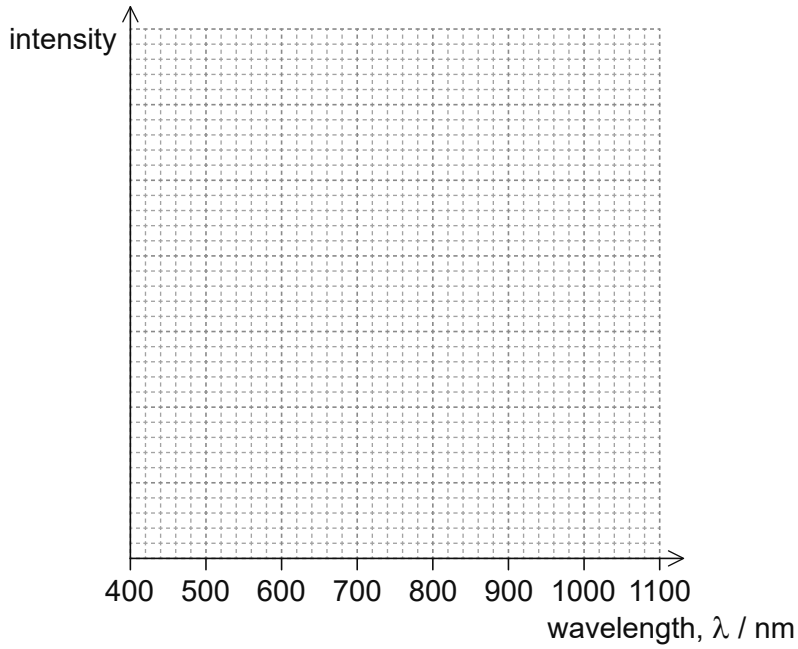
18. The surface temperature of the star Epsilon Indi is 4600 K.

(a) (i) Determine the peak wavelength of the radiation emitted by Epsilon Indi. [1]

. . . . . .

. . . . . .

(ii) Using the axis, draw the variation with wavelength of the intensity of the radiation emitted by Epsilon Indi. [2]



(Option D continues on the following page)

(Option D, question 18 continued)

(iii) The following data are available for the Sun.

Surface temperature	$= 5800\ \text{K}$
Luminosity	$= L_\odot$
Mass	$= M_\odot$
Radius	$= R_\odot$

Epsilon Indi has a radius of $0.73\ R_\odot$. Show that the luminosity of Epsilon Indi is $0.2\ L_\odot$. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

(b) Epsilon Indi is a main sequence star. Show that the mass of Epsilon Indi is $0.64\ M_\odot$. [1]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

(c) The Sun will spend about nine billion years on the main sequence. Calculate how long Epsilon Indi will spend on the main sequence. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

(Option D continues on the following page)

(Option D, question 18 continued)

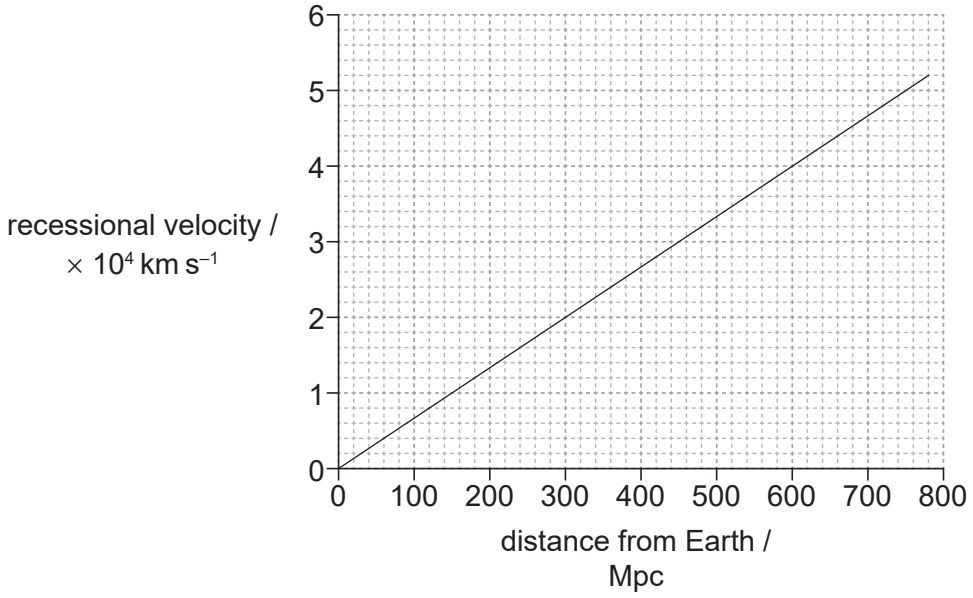
(d) Describe the stages in the evolution of Epsilon Indi from the point when it leaves the main sequence until its final stable state. [3]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

(Option D continues on the following page)

(Option D continued)

19. The graph shows the variation with distance from the Earth of the recessional velocities of distant galaxies.



(a) Outline how Hubble measured the recessional velocities of galaxies. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

(b) Use the graph to determine the age of the universe in s. [3]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

(Option D continues on the following page)

(Option D continued)

20. (a) Outline what is meant by dark energy. [2]

. . . . . .
. . . . . .
. . . . . .
. . . . . .

(b) State **two** candidates for dark matter. [2]

. . . . . .
. . . . . .

21. (a) Show that the temperature of the universe is inversely proportional to the cosmic scale factor. [3]

. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .
. . . . . .

(b) The present temperature of the cosmic microwave background (CMB) radiation is 3 K. Estimate the size of the universe relative to the present size of the universe when the temperature of the CMB was 300 K. [1]

. . . . . .
. . . . . .

End of Option D

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

Answers written on this page
will not be marked.

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

Answers written on this page
will not be marked.