Physics
Higher level
Paper 3

Tuesday 16 May 2017 (morning)

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

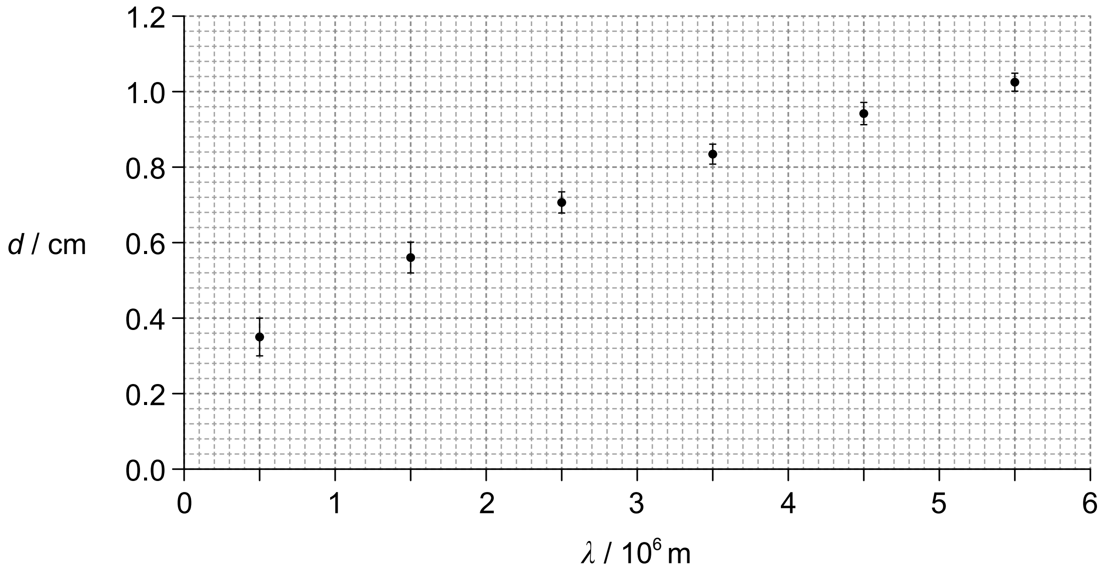
2217 – 6515

37 pages

Section A

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

1. A radio wave of wavelength λ is incident on a conductor. The graph shows the variation with wavelength λ of the maximum distance d travelled inside the conductor.



(a) Suggest why it is unlikely that the relation between d and λ is linear. [1]

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(This question continues on the following page)

(Question 1 continued)

(b) For $\lambda = 5.0 \times 10^5$ m, calculate the

(i) fractional uncertainty in d. [2]

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(ii) percentage uncertainty in d^2. [1]

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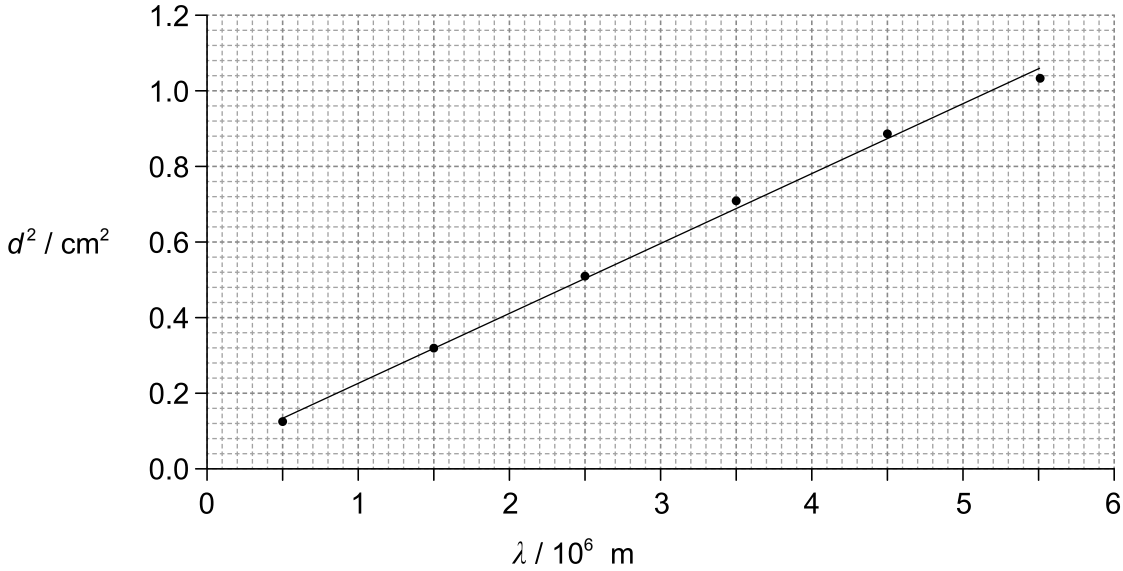
(This question continues on the following page)

(Question 1 continued)

(c) The graph shows the variation with wavelength λ of d^2. Error bars are not shown and the line of best-fit has been drawn.



A student states that the equation of the line of best-fit is $d^2 = a + b\lambda$. When d^2 and λ are expressed in terms of fundamental SI units, the student finds that $a = 0.040 \times 10^{-4}$ and $b = 1.8 \times 10^{-11}$.

(i) State the fundamental SI unit of the constant *a* and of the constant *b*. [2]

a: . . . .

b: . . . .

(ii) Determine the distance travelled inside the conductor by very high frequency electromagnetic waves. [2]

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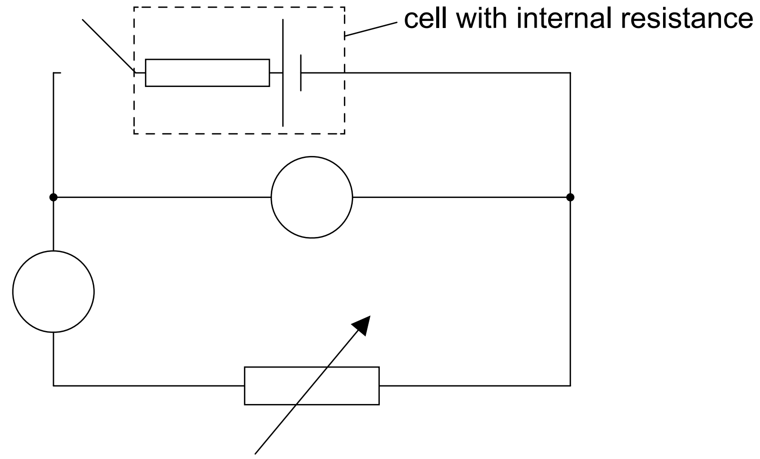
2. The circuit shown may be used to measure the internal resistance of a cell.

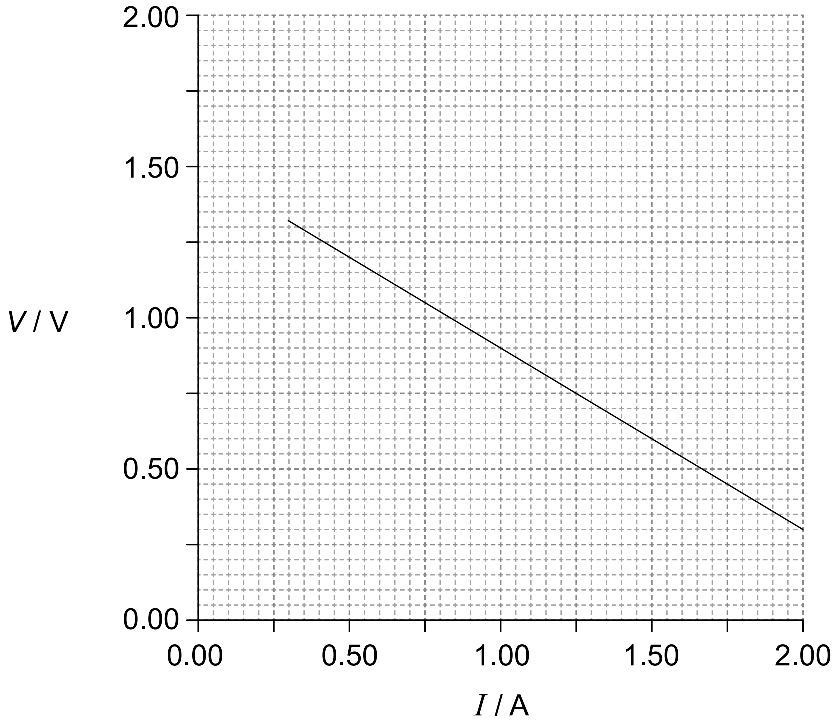


(a) An ammeter and a voltmeter are connected in the circuit. Label the ammeter with the letter A and the voltmeter with the letter V. [1]

(This question continues on the following page)

(Question 2 continued)

(b) In one experiment a student obtains the following graph showing the variation with current I of the potential difference V across the cell.



Using the graph, determine the best estimate of the internal resistance of the cell. [3]

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(This question continues on the following page)

(Question 2 continued)

(c) The ammeter used in the experiment in (b) is an analogue meter. The student takes measurements without checking for a “zero error” on the ammeter.

(i) State what is meant by a zero error. [1]

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(ii) After taking measurements the student observes that the ammeter has a positive zero error. Explain what effect, if any, this zero error will have on the calculated value of the internal resistance in (b). [2]

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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. (a) State **one** prediction of Maxwell's theory of electromagnetism that is consistent with special relativity. [1]

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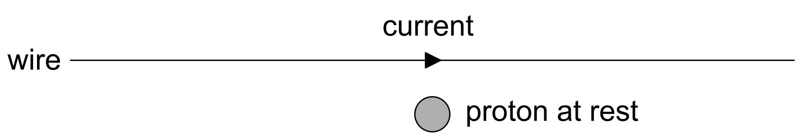
(b) A current is established in a long straight wire that is at rest in a laboratory.



A proton is at rest relative to the laboratory and the wire.

Observer X is at rest in the laboratory. Observer Y moves to the right with constant speed relative to the laboratory. Compare and contrast how observer X and observer Y account for any non-gravitational forces on the proton. [3]

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(Option A continues on the following page)

(Option A continued)

4. Muons are unstable particles with a proper lifetime of 2.2 μs. Muons are produced 2.0 km above ground and move downwards at a speed of 0.98*c* relative to the ground. For this speed $\gamma = 5.0$. Discuss, with suitable calculations, how this experiment provides evidence for time dilation. [3]

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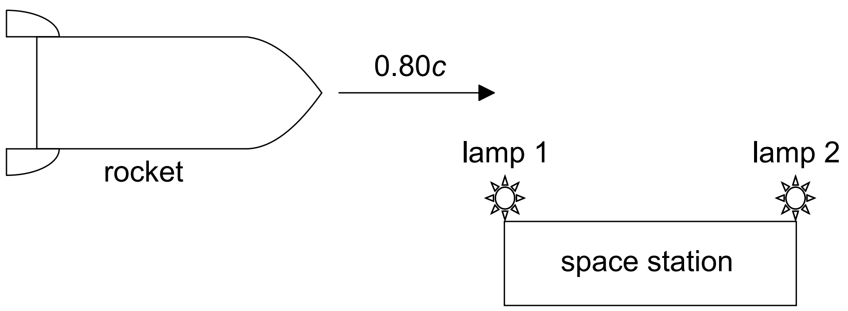
(Option A continues on the following page)

(Option A continued)

5. A rocket of proper length 450 m is approaching a space station whose proper length is 9.0 km. The speed of the rocket relative to the space station is $0.80c$.



(not to scale)

X is an observer at rest in the space station.

(a) (i) Calculate the length of the rocket according to X. [2]

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(ii) A space shuttle is released from the rocket. The shuttle moves with speed $0.20c$ **to the right** according to X. Calculate the **velocity** of the shuttle relative to the rocket. [2]

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(Option A continues on the following page)

(Option A, question 5 continued)

(b) Two lamps at opposite ends of the space station turn on at the same time according to X. Using a Lorentz transformation, determine, according to an observer at rest in the rocket,

(i) the time interval between the lamps turning on. [2]

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(ii) which lamp turns on first. [1]

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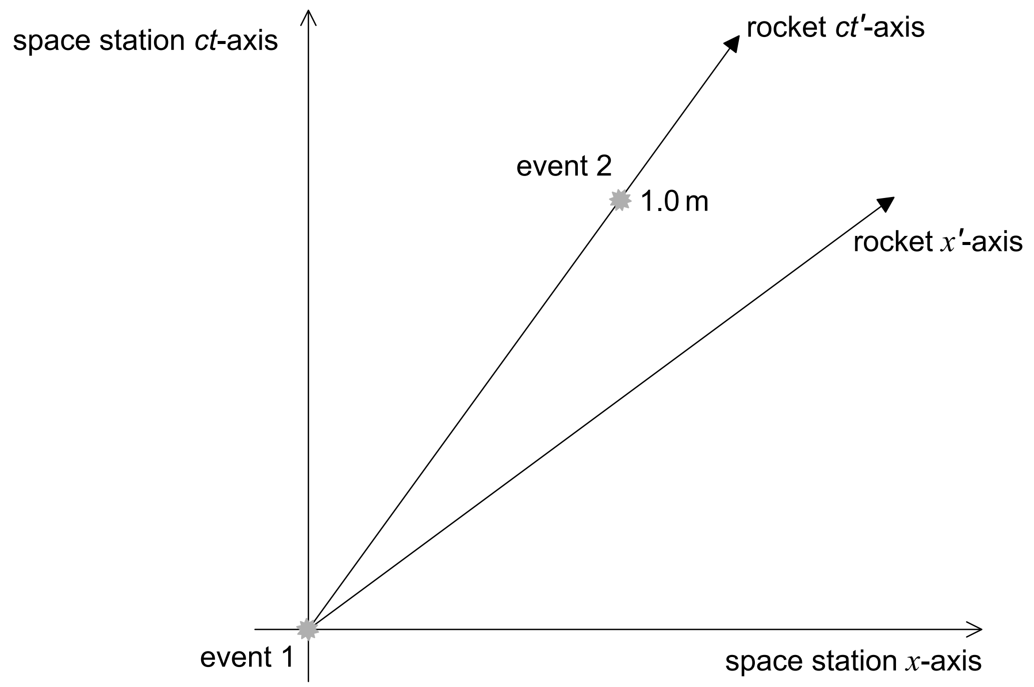
(Option A continues on the following page)

(Option A, question 5 continued)

(c) The rocket carries a different lamp. Event 1 is the flash of the rocket's lamp occurring at the origin of **both** reference frames. Event 2 is the flash of the rocket's lamp at time $ct' = 1.0$ m according to the rocket. The coordinates for event 2 for observers in the space station are x and ct.



(i) On the diagram label the coordinates x and ct. [2]

(ii) State and explain whether the ct coordinate in (c)(i) is less than, equal to **or** greater than 1.0 m. [2]

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(Option A continues on the following page)

(Option A, question 5 continued)

(iii) Calculate the value of $c^2t^2 - x^2$. [2]

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6. A lambda Λ^0 particle at rest decays into a proton p and a pion π^- according to the reaction

$$\Lambda^0 \rightarrow \mathrm{p} + \pi^-$$

where the rest energy of p = 938 MeV and the rest energy of π^- = 140 MeV.

The speed of the pion after the decay is 0.579*c*. For this speed $\gamma = 1.2265$. Calculate the speed of the proton. [4]

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(Option A continues on the following page)

(Option A continued)

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

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(ii) Show that the surface area A of the sphere corresponding to the event horizon is given by

$$A = \frac{16\pi G^2 M^2}{c^4}.$$ [1]

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(iii) Suggest why the surface area of the event horizon can never decrease. [1]

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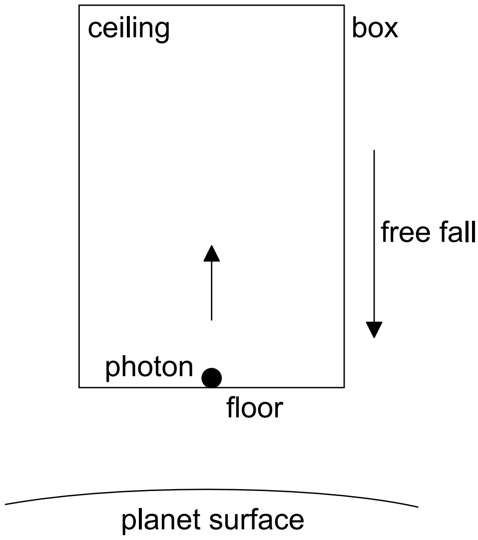
(Option A continues on the following page)

(Option A, question 7 continued)

(b) The diagram shows a box that is falling freely in the gravitational field of a planet.



A photon of frequency f is emitted from the floor of the box and is received at the ceiling. State and explain the frequency of the photon measured at the ceiling. [3]

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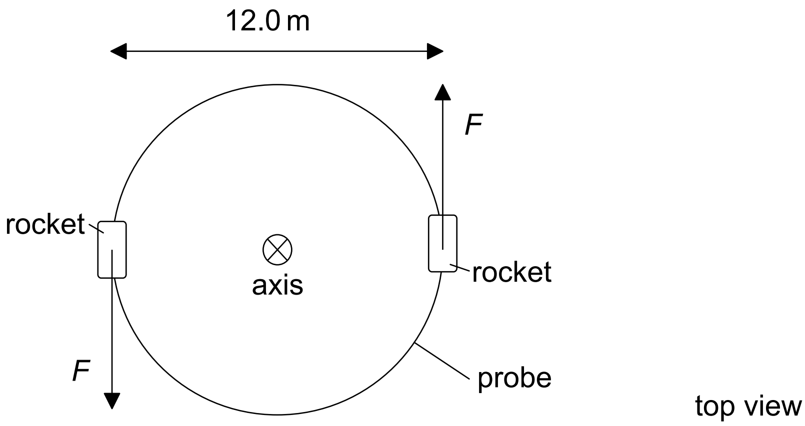
End of Option A

Option B — Engineering physics

8. A cylindrical space probe of mass 8.00×10^2 kg and diameter 12.0 m is at rest in outer space.



Rockets at opposite points on the probe are fired so that the probe rotates about its axis. Each rocket produces a force $F = 9.60 \times 10^3$ N. The moment of inertia of the probe about its axis is 1.44×10^4 kg m^2.

(a) (i) Deduce the linear acceleration of the centre of mass of the probe. [1]

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(ii) Calculate the resultant torque about the axis of the probe. [2]

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(b) The forces act for 2.00 s. Show that the final angular speed of the probe is about 16 rad s^{-1}. [2]

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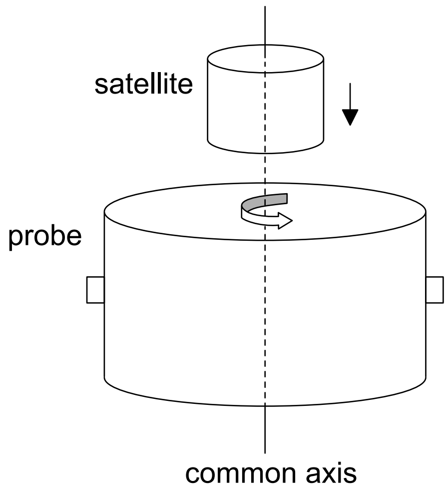
(Option B continues on the following page)

(Option B, question 8 continued)

(c) The diagram shows a satellite approaching the rotating probe with negligibly small speed. The satellite is not rotating initially, but after linking to the probe they both rotate together.



The moment of inertia of the satellite about its axis is $4.80 \times 10^3\ \text{kg m}^2$. The axes of the probe and of the satellite are the same.

(i) Determine the final angular speed of the probe–satellite system. [2]

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(ii) Calculate the loss of rotational kinetic energy due to the linking of the probe with the satellite. [3]

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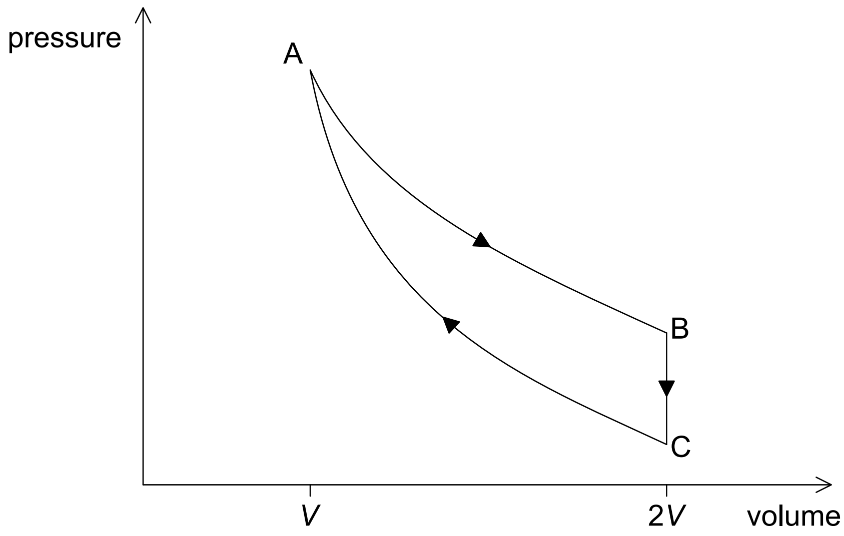
(Option B continues on the following page)

(Option B continued)

9. A heat engine operates on the cycle shown in the pressure–volume diagram. The cycle consists of an isothermal expansion AB, an isovolumetric change BC and an adiabatic compression CA. The volume at B is double the volume at A. The gas is an ideal monatomic gas.



At A the pressure of the gas is 4.00×10^{6} Pa, the temperature is 612 K and the volume is 1.50×10^{-4} m^{3}. The work done by the gas during the isothermal expansion is 416 J.

(a) (i) Justify why the thermal energy supplied during the expansion AB is 416 J. [1]

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(ii) Show that the temperature of the gas at C is 386 K. [2]

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(Option B continues on the following page)

(Option B, question 9 continued)

(iii) Show that the thermal energy removed from the gas for the change BC is approximately 330 J. [2]

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(iv) Determine the efficiency of the heat engine. [2]

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(b) State and explain at which point in the cycle ABCA the entropy of the gas is the largest. [3]

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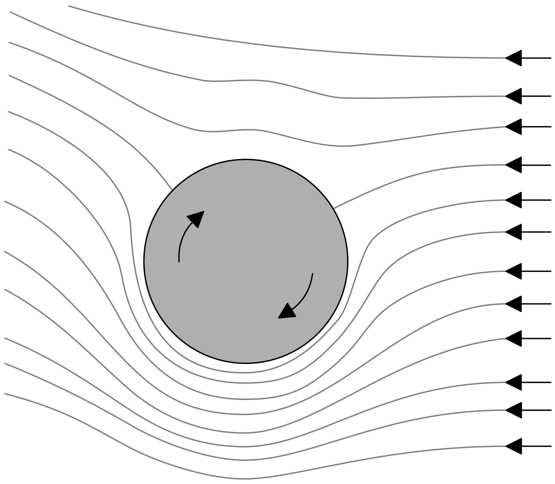
(Option B continues on page 21)

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

Answers written on this page will not be marked.

(Option B continued from page 19)

10. A ball is moving in still air, spinning clockwise about a horizontal axis through its centre. The diagram shows streamlines around the ball.



(a) The surface area of the ball is $2.50 \times 10^{-2}\,m^2$. The speed of air is $28.4\,m\,s^{-1}$ under the ball and $16.6\,m\,s^{-1}$ above the ball. The density of air is $1.20\,kg\,m^{-3}$.

(i) Estimate the magnitude of the force on the ball, ignoring gravity. [2]

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(ii) On the diagram, draw an arrow to indicate the direction of this force. [1]

(b) State **one** assumption you made in your estimate in (a)(i). [1]

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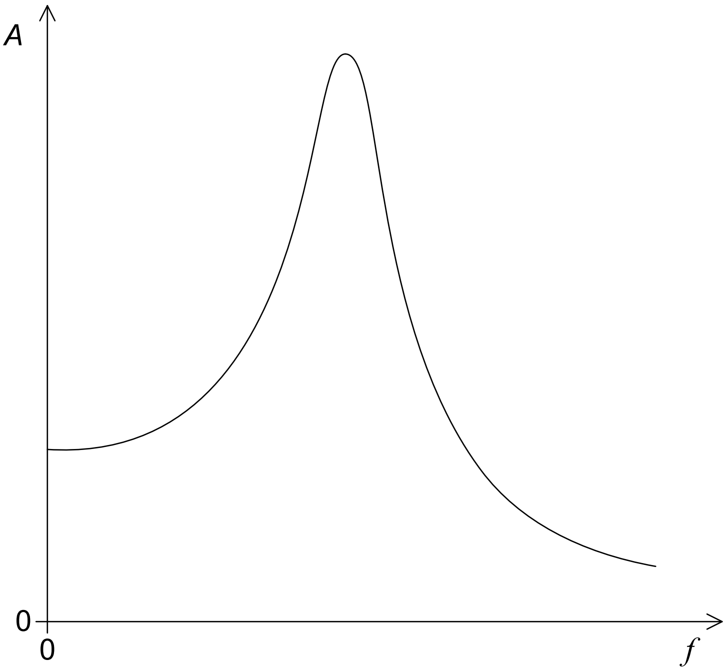
(Option B continues on the following page)

(Option B continued)

11. A driven system is lightly damped. The graph shows the variation with driving frequency f of the amplitude A of oscillation.

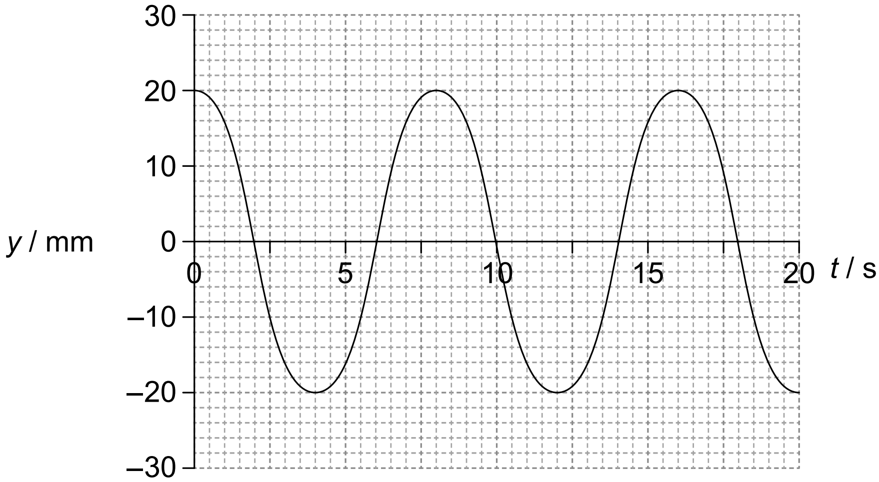


(a) On the graph, sketch a curve to show the variation with driving frequency of the amplitude when the damping of the system **increases**. [2]

(Option B continues on the following page)

(Option B, question 11 continued)

(b) A mass on a spring is forced to oscillate by connecting it to a sine wave vibrator. The graph shows the variation with time *t* of the resulting displacement *y* of the mass. The sine wave vibrator has the same frequency as the natural frequency of the spring–mass system.



(i) State and explain the displacement of the sine wave vibrator at $t = 8.0$ s. [2]

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(ii) The vibrator is switched off and the spring continues to oscillate. The *Q* factor is 25.

Calculate the ratio $\frac{\text{energy stored}}{\text{power loss}}$ for the oscillations of the spring–mass system. [2]

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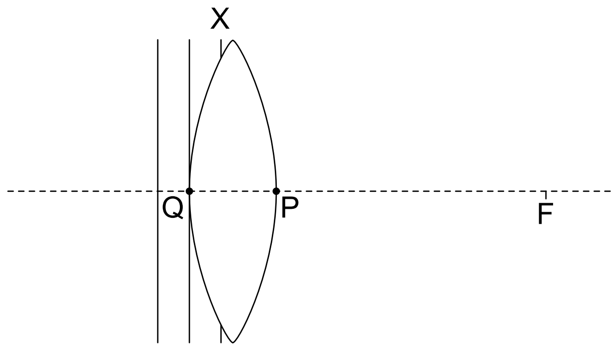
End of Option B

Option C — Imaging

12. The diagram shows planar wavefronts incident on a converging lens. The focal point of the lens is marked with the letter F.



Wavefront X is incomplete. Point Q and point P lie on the surface of the lens and the principal axis.

(a) On the diagram, sketch the

(i) part of wavefront X that is inside the lens. [1]

(ii) wavefront in air that passes through point P. Label this wavefront Y. [1]

(b) Explain your sketch in (a)(i). [2]

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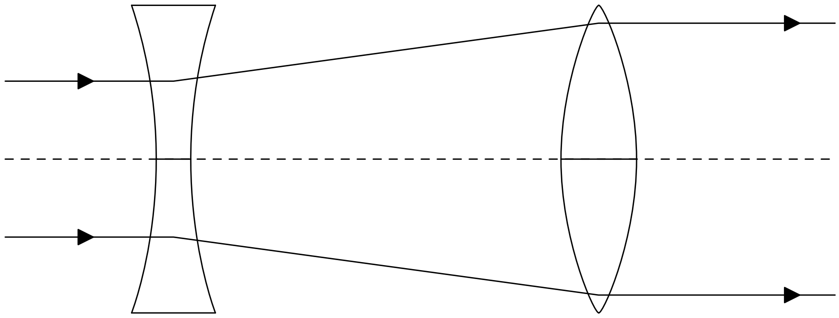
(Option C continues on the following page)

(Option C, question 12 continued)

(c) Two parallel rays are incident on a system consisting of a diverging lens of focal length 4.0 cm and a converging lens of focal length 12 cm.



The rays emerge parallel from the converging lens. Determine the distance between the two lenses. [2]

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(Option C continues on the following page)

(Option C continued)

13. Two converging lenses placed a distance 90 cm apart are used as a simple astronomical refracting telescope at normal adjustment. The angular magnification of this arrangement is 17.

(a) Determine the focal length of each lens. [2]

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(b) The telescope is used to form an image of the Moon. The angle subtended by the image of the Moon at the eyepiece is 0.16 rad. The distance to the Moon is 3.8×10^{8} m. Estimate the diameter of the Moon. [3]

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(c) State **two** advantages of the use of satellite-borne telescopes compared to Earth-based telescopes. [2]

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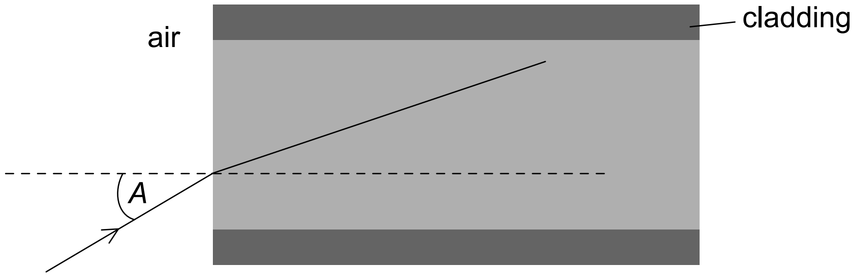
(Option C continues on the following page)

(Option C continued)

14. (a) The diagram shows a ray of light in air that enters the core of an optic fibre.



The ray makes an angle *A* with the normal at the air–core boundary. The refractive index of the core is 1.52 and that of the cladding is 1.48.

Determine the largest angle *A* for which the light ray will stay within the core of the fibre. [3]

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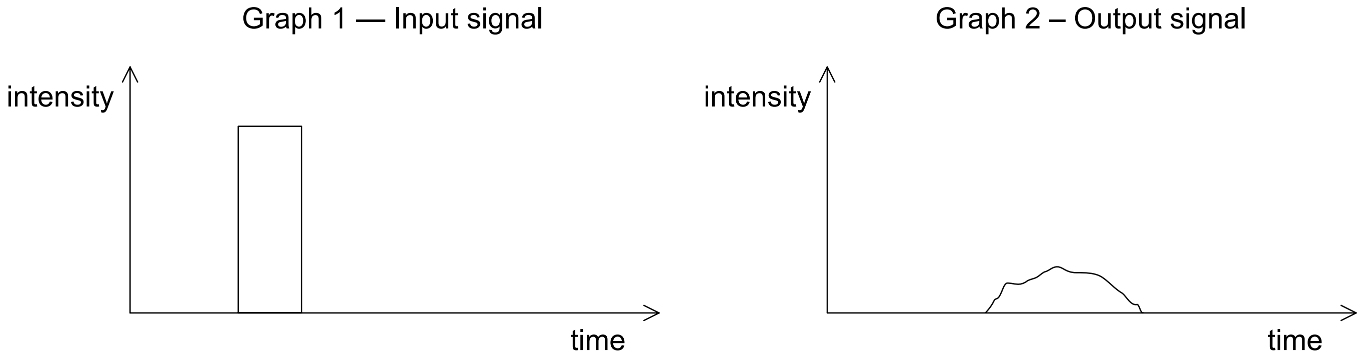
(Option C continues on the following page)

(Option C, question 14 continued)

(b) The graphs show the variation with time of the intensity of a signal that is being transmitted through an optic fibre. Graph 1 shows the input signal to the fibre and Graph 2 shows the output signal from the fibre. The scales of both graphs are identical.



(i) Identify the features of the output signal that indicate the presence of attenuation and dispersion. [2]

attenuation: . . . .

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dispersion: . . . .

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(ii) The length of the optic fibre is 5.1 km. The input power of the signal is 320 mW. The output power is 77 mW. Calculate the attenuation per unit length of the fibre in dB km^{-1}. [2]

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(Option C continues on the following page)

(Option C continued)

15. (a) State a typical frequency used in medical ultrasound imaging. [1]

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(b) Describe how an ultrasound transducer produces ultrasound. [3]

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(Option C continues on the following page)

(Option C, question 15 continued)

(c) The density of muscle is 1075 kg m^{-3} and the speed of ultrasound in muscle is 1590 m s^{-1}.

(i) Calculate the acoustic impedance Z of muscle. [1]

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(ii) Ultrasound of intensity 0.012 W cm^{-2} is incident on a water–muscle boundary. The acoustic impedance of water is 1.50×10^6 kg m^{-2} s^{-1}.

The fraction of the incident intensity that is reflected is given by

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

where Z_1 and Z_2 are the acoustic impedances of medium 1 and medium 2.

Calculate the intensity of the reflected signal. [2]

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16. In nuclear magnetic resonance (NMR) imaging radio frequency electromagnetic radiation is detected by the imaging sensors. Discuss the origin of this radiation. [3]

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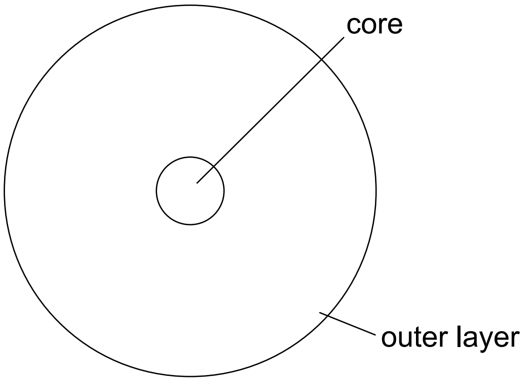
End of Option C

Option D — Astrophysics

17. The diagram shows the structure of a typical main sequence star.



(a) State the most abundant element in the core and the most abundant element in the outer layer. [2]

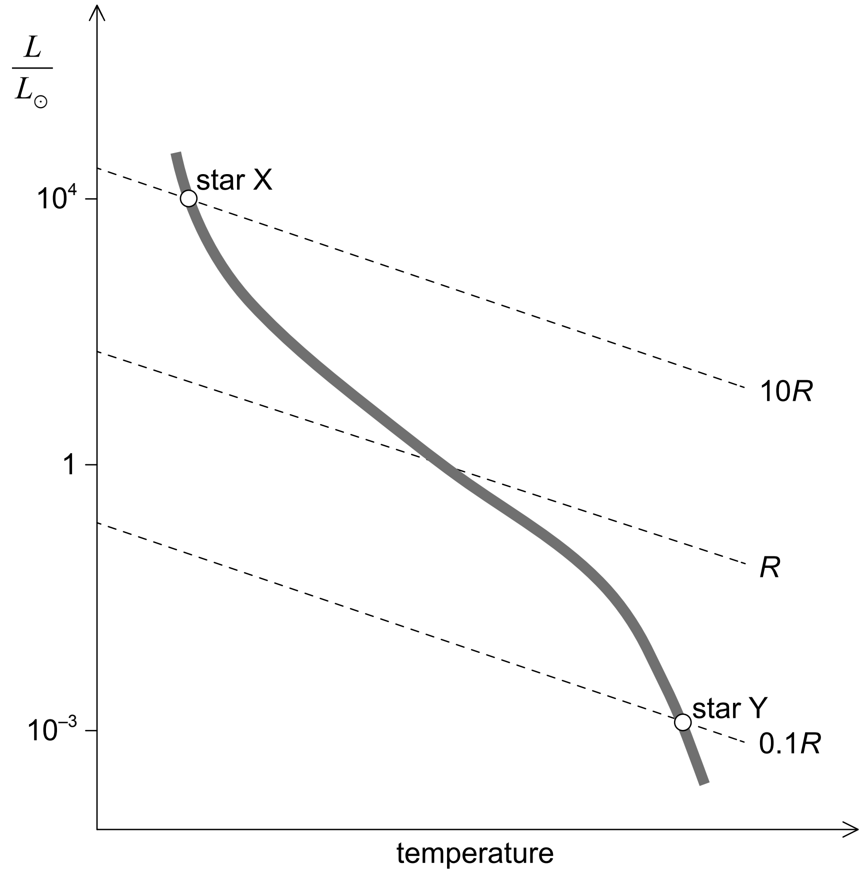
core: . . . .

outer layer: . . . .

(Option D continues on the following page)

(Option D, question 17 continued)

(b) The Hertzsprung–Russell (HR) diagram shows two main sequence stars X and Y and includes lines of constant radius. R is the radius of the Sun.



Using the mass–luminosity relation and information from the graph, determine the ratio $\dfrac{\text{density of star X}}{\text{density of star Y}}$. [3]

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(Option D continues on the following page)

(Option D, question 17 continued)

(c) Star X is likely to evolve into a neutron star.

(i) On the HR diagram in (b), draw a line to indicate the evolutionary path of star X. [1]

(ii) Outline why the neutron star that is left after the supernova stage does not collapse under the action of gravitation. [1]

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(iii) The radius of a typical neutron star is 20 km and its surface temperature is 10^6 K. Determine the luminosity of this neutron star. [2]

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(iv) Determine the region of the electromagnetic spectrum in which the neutron star in (c)(iii) emits most of its energy. [2]

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18. (a) Describe what is meant by the Big Bang model of the universe. [2]

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(Option D continues on the following page)

(Option D, question 18 continued)

(b) State **two** features of the cosmic microwave background (CMB) radiation which are consistent with the Big Bang model. [2]

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(c) A particular emission line in a distant galaxy shows a redshift $z = 0.084$.

The Hubble constant is $H_0 = 68\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$.

(i) Determine the distance to the galaxy in Mpc. [2]

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(ii) Describe how type Ia supernovae could be used to measure the distance to this galaxy. [3]

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(Option D continues on the following page)

(Option D continued)

19. (a) (i) Derive, using the concept of the cosmological origin of redshift, the relation

$$T \propto \frac{1}{R}$$

between the temperature T of the cosmic microwave background (CMB) radiation and the cosmic scale factor R. [2]

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(ii) The present temperature of the CMB is 2.8 K. This radiation was emitted when the universe was smaller by a factor of 1100. Estimate the temperature of the CMB at the time of its emission. [2]

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(b) State how the anisotropies in the CMB distribution are interpreted. [1]

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(Option D continues on the following page)

(Option D continued)

20. (a) Describe what is meant by dark matter. [2]

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(b) The distribution of mass in a spherical system is such that the density ρ varies with distance r from the centre as

$$\rho = \frac{k}{r^2}$$

where k is a constant.

Show that the rotation curve of this system is described by

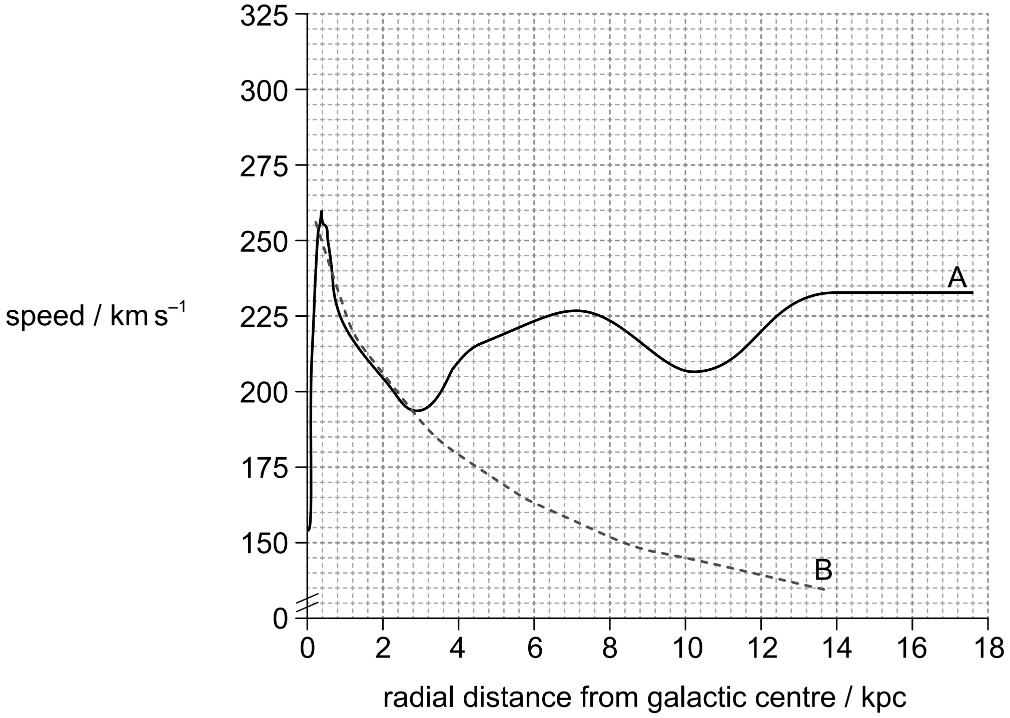
$$v = \text{constant}.$$ [1]

. . . .
. . . .

(Option D continues on the following page)

(Option D, question 20 continued)

(c) Curve A shows the actual rotation curve of a nearby galaxy. Curve B shows the predicted rotation curve based on the visible stars in the galaxy.



Explain how curve A provides evidence for dark matter. [2]

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End of Option D

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