Corrected V2.

SENIOR PHYSICS CHALLENGE
March 2024
SOLUTIONS

Marking

The mark scheme is prescriptive, but markers must make some allowances for alternative answers. It is not possible to provide notes of alternative solutions that students devise, since there is no opportunity to mark a selection of students' work before final publication. Hence, alternative valid physics should be given full credit. If in doubt on a technical point, email rh584@cam.ac.uk .

A positive view should be taken for awarding marks for good physics ideas are rewarded. These are problems, not mere questions. Students should be awarded for progress, even if they do not make it quite to the end point, as much as possible. Be consistent in your marking.

Benefit of the doubt is NOT to be given for scribble.

The worded explanations may be quite long in the mark scheme to help students understand. Much briefer responses than these solutions would be expected from candidates.

A value quoted at the end of a section must have the units included. Candidates lose a mark the first time that they fail to include a unit, but not on subsequent occasions, except where it is a specific part of the question.

The paper is not a test of significant figures. Significant figures are related to the number of figures given in the question. A single mark is lost the first time that there is a gross inconsistency (more than 3 sf **out**) in the final answer to a question. Almost all the answers can be given correctly to 2 sf. The mark scheme often give 2 or 3 sf: either will do, or even less. If there is some modest rounding error in their answer then give them the mark. There is time pressure and so if they are on track for the answer then award the mark.

ecf: this is allowed in numerical sections provided that unreasonable answers are not being obtained. However, there are several questions where the initial answers are easily obtained an if they are wrong then there is no reason to do a lot of ecf. They should get easy questions right.

owtte: "or words to that effect" – is the key physics idea present and used?

Section A: Multiple Choice

Question 1. C
Question 2. B
Question 3. D
Question 4. B
Question 5. B
Question 6. A
Question 7. A
Question 8. C
Question 9. C
Question 10. C

Q11. **(a)** **(i)** $V = \frac{E}{Q} = \frac{2.4\times10^{10}}{20} = 1.2 \times 10^9$ V ✓

(ii) Breakdown = $1.0 \times 10^4 \, \frac{\text{V}}{\text{cm}} = 1.0 \times 10^6 \, \frac{\text{V}}{\text{m}} = \frac{1.2\times10^9}{h}$.

So $h = 1.2$ km ✓

(b) $Q = It = 1200 \times 120 = 1.44 \times 10^5$

So, no. of thunderstorms $N = \frac{1.44\times10^5}{20} = 7.2 \times 10^3$ ✓

(c) 7200 thunderstorms each producing one strike of 2.4×10^{10} J every 120 seconds is 1.44×10 W.

Volume of atmosphere = surface area × height

$= 4\pi \times (6.37 \times 10^6)^2 \times 1000 \text{ m}^3$

Dividing power/volume gives $\approx 2.8 = 3$ μW m^{-3} ✓

Total 4

Q12. **(a)** The radius is smaller, circumference is smaller, so the wheel rotates faster and the speed appears faster than the true speed.

e.g. at 70 mph the speedometer reads 80 mph ✓

(b) $\frac{l}{2\pi r_0} = N_0$ in a time T. And $\frac{l}{2\pi r_1} = N_1$ rotations in same time T.

So $r_0 N_0 = r_1 N_1$ and so $N_0 = \frac{r_1}{r_0} N_1$ and so $v_0 = \frac{r_1}{r_0} \times 70$ mph (argument) ✓

$$v_1 = \frac{\frac{621.5}{2} - 8.5 + 1.6}{\frac{621.5}{2}} \times 70 \text{ mph} = 68.4 \text{ mph}$$

mark for the setup for using the different tread depths correctly ✓

If the diameter of 621.5 mm is taken for the radius, the result is

$$v_1 = \frac{621.5 - 8.5 + 1.6}{621.5} \times 70 \text{ mph} = \frac{614.6}{621.5} \times 70 = 69.2 \text{ mph}$$

Which still gets the mark – so allow $68.4 = 68$ mph or $69.2 = 69$ mph ✓

Total 4

Q13. (a) The wire heats up in 5 s.

$Pt = mc\theta$ so $1100 \times 5 = m \times 450 \times (300 - 20)$ (values) ✓

and so $m = 44$ g ✓

(b) $P = \frac{V^2}{R}$ and hence $R = \frac{V^2}{P} = \frac{230^2}{1100} = 48.1 = 48\ \Omega$ idea and result ✓✓

(c) $\rho = \frac{\pi r^2 R}{\ell} \left(= \frac{\pi \times \left(0.5 \times 10^{-3}\right)^2 \times 48}{\ell} \right)$ and density $d = \frac{m}{A\ell}$

Eliminating ℓ $\rho = \frac{A^2 R d}{m} = \frac{\pi^2 r^4 R d}{m} = \frac{\pi^2 \times \left(0.5 \times 10^{-3}\right)^4 \times 48 \times 8310}{44 \times 10^{-3}}$ ✓

$\rho = 5.6 \times 10^{-6} = 6 \times 10^{-6}\ \Omega$ m ✓

(d) As the temperature rises, for a metal one would expect the resistance to increase approximately linearly with the temperature, and as an indication, proportional to the kelvin temperature. So the resistance might double, the current halve and the power halve. However, the temperature would continue to rise. In fact, for nichrome, the alloy is chosen as its resistance increases very little over the temperature range of operation and so these effects would be smaller than for an elemental wire.

(two distinct and clear points – no waffle) ✓✓

Total 8

Q14. (a) The mass: $m = \rho \qquad \frac{\ }{3} \times 40 \quad \times 40 = 5.3 \times 10^7$ kg ✓✓

(b) (i) $\ell = \frac{40}{3} = 13.3$ m and the mass is 3.8×10^6 kg ✓✓

(ii) $h_1 = 6.7$ m, $h_2 = 20$ m, $h_3 = 33.3$ m ✓

(iii) $W = 4 \times 3.8 \times 10^6 \times 9.8 \times (20 - 6.7)$ ...

$+1 \times 3.8 \times 10^6 \times 9.8 \times (33.3 - 6.7)$

$= 3 \times 10^9$ J ✓

This calculation raises the CM of the upper blocks from their position of 6.7 m high when on the ground. This is perhaps a dubious addition to an estimation and the simple answer obtained without this subtlety,

$W = 4 \times 3.8 \times 10^6 \times 9.8 \times 20 + 1 \times 3.8 \times 10^6 \times 9.8 \times 33.3$

$= 4.2 \times 10^9$ J is quite acceptable.

(the blocks which rest on the ground would have to be constructed from small bricks to build these enormous blocks).

(c) $\tan(\theta) = 2$ so $\theta = 63°$ ✓

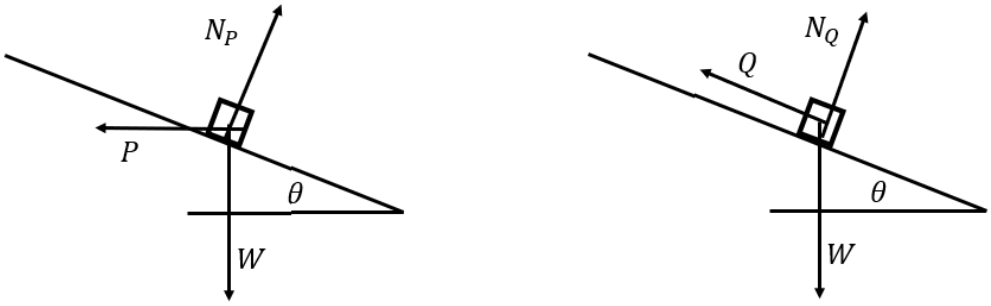
(d) $N = \frac{3 \times 10^9}{365} \div 800 \times 4.18 \times 10^3 = 3.4 \approx 4$ labourers! ✓

$N = \frac{4.2 \times 10^9}{365} \div 800 \times 4.18 \times 10^3 = 2.4 \approx 2 - 3$ labourers!

Anything between 2 and 5 labourers is fine.

Total 8

Q15. **(a)** Each diagram must show the three forces. N_P and N_Q are not the same value, but may just be shown as N. This is fine as long as a single label N is not used in the equations written.



✓✓

(b) To avoid N_P resolve parallel to the slope: $Wsin(\theta) = Pcos(\theta)$
Similarly avoid N_Q: $Wsin(\theta) = Q$ ✓

(c) To eliminate θ we need to square and add and use $\sin^2\theta + \cos^2\theta = 1$

$Q = Pcos\theta$ so $\left(\frac{Q}{P}\right)^2 + \left(\frac{Q}{W}\right)^2 = \cos^2\theta + \sin^2\theta = 1$ ✓

And then $W^2 = \frac{W^2Q^2}{P^2} + Q^2$

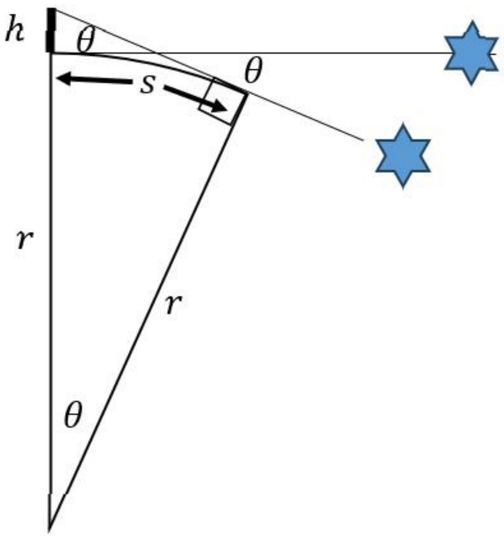
Leading to $P^2W^2 = Q^2W^2 + P^2Q^2$

Then $W^2(P^2 - Q^2) = P^2Q^2$

And hence the result $W = \frac{PQ}{(P^2-Q^2)^{\frac{1}{2}}}$

<u>Total 4</u>

Q16. **(a)** **(i)** A diagram annotated by the student is essential. Something like below.



(ii) We need an estimate of angle θ.

Assuming θ is a small angle, we can write

1. $\theta = \frac{s}{r}$
2. From the top left small triangle,
   $\theta \approx \frac{h}{\frac{s}{2}} = \frac{2h}{s}$

Eliminating s from these equations,

$$\theta = \frac{2h}{r\theta}$$

So that $\boldsymbol{\theta} = \sqrt{\frac{\mathbf{2h}}{\mathbf{r}}}$

There are several approaches that can be taken but they will all lead to this. Some trig approximations can be made, such as, for example $\frac{r}{r+h} = cos\theta$ and using an approximation for cos, as $cos\theta \approx 1 - \frac{\theta^2}{2}$

Then $1 - \frac{\theta^2}{2} \approx \frac{r}{r+h}$ and rearranging, this also gives $\theta = \sqrt{\frac{2h}{r}}$ when $h \ll r$.

Or using $\sin^2\theta = 1 - \cos^2\theta$ and substituting for $cos\theta = \frac{r}{r+h}$ and again with $h \ll r$ the result is obtained. ✓✓

✓✓

(b). Numerically, $\theta = \sqrt{\frac{2}{6.37\times10^6}}\left(\sqrt{3.5} - \sqrt{0.8}\right) = \mathbf{5.5} \times \mathbf{10}^{\ \mathbf{4}}$ **radians** ✓✓

(c). As the Earth rotes 2π radians in 24 hours, the Δt (in seconds) for sunset is given by

$\frac{\Delta t}{24\times3600} = \frac{5.5\times10^{-4}}{2\pi}$ which leads to $\Delta t = 7.5 =$ **7 or 8** **seconds** ✓✓

Marks:

- 1 or 2 from the diagram. It must be clear, so that you know which angle is θ.
- Then 3 or 2 marks for the obtaining of θ in term of h and r. **Total of 4 marks.**
- For numerical result, $\boldsymbol{\theta} = \mathbf{5.0 \times 10^{-4}}$ **radians** **2marks**
- Time after 8pm numerical results of around 7 seconds (an approximation) **2 marks**

- There could be a lot of ecf here, but you cannot reasonably be expected to work this out. So your best judgment for the marks as far as they go.
  But no benefit of the doubt or marks for effort. If they have not got it right then they can't have the marks.

<u>**Total 8**</u>

Q17. **(a)**

No. of molecules consumed by Caesar in a lifetime $= (t \times V_{\text{day}}) \times \left(\frac{\rho}{M} \times 10^3\right) \times N_{\text{A}}$

No of molecules in the oceans $= f \times (d \times 4\pi R_E^2) \times \left(\frac{\rho}{M} \times 10^3\right) \times N_{\text{A}}$

So the fraction of Caesars molecules to molecules in the water of the oceans is

$$\left[\frac{(t \times V_{\text{day}})}{f \times (d \times 4\pi R_E^2)}\right]$$

No of molecules in a mug of tea $= V_{\text{mug}} \times \left(\frac{\rho}{M} \times 10^3\right) \times N_{\text{A}}$

(b)

Therefore the number of Caesar's molecules in your mug is the fraction in the water multiplied by the number of molecules of water in your mug

$$= V_{\text{mug}} \times \left(\frac{\rho}{M} \times 10^3\right) \times N_{\text{A}} \times \left[\frac{t \times V_{\text{day}}}{f \times (d \times 4\pi \times R_E^2)}\right]$$

Marks

- 1 mark for each stage as suggested further above, up to 4 marks.

- The working will probably be done by a mixture of symbols and numbers.
- More consideration should be given to a calculation using the variables suggested than a muddle of numbers.

The numerical answer is not expected (it is given) but it is of some interest to get the students to evaluate it afterwards.

Numerically:

$V_{\text{mug}} = \frac{1}{5}$ litre $= \frac{1}{5000}$ m^3

$\rho = 10^3 \frac{\text{kg}}{\text{m}^3}$

$M = 18 \frac{\text{g}}{\text{mole}}$

$N_A = 6 \times 10^{23}$ per mole

Caesar lived to $t \approx 60$ years $= 60 \times 365$ days

$V_{\text{day}} = 2$ litres $= \frac{1}{500}$ m^3

Fraction of Earth's surface covered by water, $f = 0.6$

Depth of ocean, $d = 5000$ m

$R_E = 6.4 \times 10^6$ m

No of molecules in our mug

$$= \frac{1}{5000} \times \left(\frac{10^3}{18} \times 10^3\right) \times 6 \times 10^{23} \times \left[\frac{(365 \times 60) \times \frac{1}{500}}{0.6 \times 5 \times 10^3 \times 4\pi \times (6.4 \times 10^6)^2}\right]$$

$\approx 10^8$ molecules

Total 4

END OF SOLUTIONS