AS CHALLENGE PAPER 2017

Name	
School	

Friday 10th March

Total Mark/50

Time Allowed: ***One hour***

Attempt as many questions as you can.

Write your answers on this question paper. ***Draw diagrams****.*

Marks allocated for each question are shown in brackets on the right.

You may use any calculator.

You may use any public examination formula booklet.

Allow no more than ***6 or 7 minutes*** *for* ***section A.***

Scribbled or unclear working will not gain marks.

This paper is about problem solving. It is designed to be a challenge for the top AS physicists in the country. If you find the questions hard, they are. Do not be put off. The only way to overcome them is to struggle through and learn from them.

Good Luck.

Students*: this year this paper is being used to select students to invite to the Astronomy & Astrophysics Training Camp at Oxford Tuesday 3rd to Friday 7th April 2017. Previous experience in these subjects is not required.*

Useful constants and equations

$$c = 3.00 \times 10^8 \text{ m } s^{-1}$$
$$h = 6.63 \times 10^{-34} \text{ J s}$$
$$e = 1.60 \times 10^{-19} \text{ C}$$
$$g = 9.81 \text{ m s}^{-2}$$

surface area of a sphere $= 4\pi r^2$ volume of a sphere $= \frac{4}{3}\pi r^3$

$v^2 = u^2 + 2as$ $v = u + at$

power = force × velocity $P = E/t$ $v = f\lambda$

$V = IR$ $R = R_1 + R_2$ $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$

Answers

Qu 1	Qu 2	Qu 3	Qu 4	Qu 5	Qu 6

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Section A: Multiple Choice

Circle the correct answer to each question. Write your answers in the table on page 2.

Each question is worth 1 mark. There is only one correct answer to each question.

1. Which are the correct dimensions of force in terms of mass [M], length [L] and time [T]?

A. $\frac{\mathrm{ML}}{\mathrm{T}^2}$ B. $\frac{\mathrm{MT}^2}{\mathrm{L}}$ C. $\frac{\mathrm{ML}^2}{\mathrm{T}^2}$ D. $\frac{\mathrm{ML}^2}{\mathrm{T}}$

2. Wind tunnel experiments are carried out on model aircraft, with the results scaled up to real size aircraft. In order to determine how the lift on a wing scales up, a relation has to be found between the lift, F (a force), the area of the wing, A, the velocity of the air flow, v, and the density of air, ρ. Which of the following expression could correctly relate these quantities?

A. $F = \frac{Av^2}{\rho}$ B. $F = A^2 v\rho$ C. $F = Av^2\rho$ D. $F = Av\rho$

The LHC accelerator at CERN has two beams of protons circulating in opposite directions, with each proton in a beam having an energy of 7.0 TeV (T is terra which is 10^{12}). The circumference of the circular accelerator is 27 km and the particles are travelling at (almost) the speed of light.
The protons circulate as bunches, with 2808 bunches per beam. There are 1.15×10^{11} protons per bunch.

$$1\ \mathrm{eV} = 1.6 \times 10^{-19}\ \mathrm{J}$$

3. What is the energy of each beam in joules?

A. 180 MJ B. 360 MJ C. 5.2×10^{-5} J D. 360 J

4. What is the current in each beam?

A. 0.6 μA B. 6 μA C. 6 mA D. 0.6 A

5. The energy stored in the LHC at any one moment is about 10 GJ, mainly in the magnetic fields of the 1200 magnets. If the mass of a magnet is about 35×10^3 kg and the energy stored was used to move the magnets in the form of kinetic energy, what would be the speed of a single magnet?

A. 6.9 m s^{-1} B. 11 m s^{-1} C. 15 m s^{-1} D. 22 m s^{-1}

6. The energy content of an explosive called TNT is 4.7 MJ kg^{-1}. What mass of TNT is equivalent to the 10 GJ of energy stored in the LHC?

A. 2.1 kg B. 21 kg C. 2100 kg D. 2.1×10^5 kg

Section B: Written Answers

Question 7.

When cutting a hard piece of cheese with a knife, a rocking motion of the knife is often used. Give an explanation why, even with a sharp knife, it is easier to cut cheese in this way.

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Question 8.

A spider of mass m hangs from the end of a single, elastic, thread obeying Hooke's Law, of a web attached to the ceiling of a room. The extension of the thread is equal to the natural length of the thread ℓ_o, when the spider is at the bottom end of the thread.

a) Explain why the work done by spider in climbing the thread all the way to the ceiling is less than the work done to climb a vertical distance $2\ell_o$ without the thread.

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b) What fraction of the work that would be required to climb to the ceiling does the spider save by using the elastic thread to climb up?

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Question 9.

a) A mass can be measured on Earth using both a spring balance and a lever balance. If these two instruments are used on the Moon, what difference would it make to the value of the weight that you measure? Explain your answer.

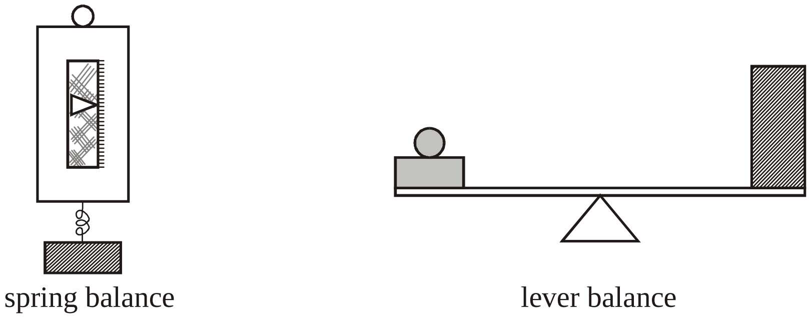

Figure 1. Examples of two types of balance used to weigh objects.

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b) A lever balance of the same type as shown above in Figure 1, is used for weighing objects. It consists of two small, unequal pans at the ends of a beam balanced on a fulcrum. The arms of the balance are of unequal length, but the beam remains horizontal when the pans are not loaded. An object of true weight W is to be weighed. When placed in one pan, the balance is levelled with a weight W_1 in the other pan, and in the other pan, the weight W is balanced by a weight W_2.
Find a symbolic expression that relates W to W1 and W2 before inserting numbers.
If $W_1 = 1.22$ kg and $W_2 = 1.90$ kg, what is the true weight W?

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Question 10.

In 1639 J. Marc Marci (de Crownland) laid down the rules for the collision of elastic and inelastic bodies, which were again investigated by Wallis, Wren and Huygens in the late 1660s. Their work was made more accessible by Wallis in *Mechanica, Pars Tertia*, 1671, and through written works of other authors of this period. Here is a problem on the topic.

A particle is incident on a smooth, rigid, plane surface at angle of incidence θ and reflects inelastically with some loss of energy at angle of reflection ϕ. The initial speed is u; the final speed is v. Half of the kinetic energy is lost in the collision with the wall. In addition, the normal component of velocity is reduced by a factor $\sqrt{3}$ on collision with the wall.

a) Show the path of the particle on an annotated diagram, giving the angles and speeds. [2]

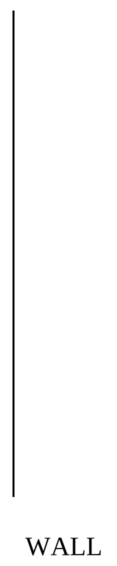

Figure 2. Diagram to be annotated for the path of the particle.

b) Using the information given, write down three equations connecting

i. the initial and final speeds,
ii. the components of velocities parallel to the wall, and
iii. the components of velocities perpendicular to the wall.

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c) Solve these three equations to determine the values of the angles θ and ϕ which are required to satisfy these conditions.

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Question 11.

An early measurement of the speed of light was made by a Danish scientist Ole Rømer in the 1670s. He observed the period of orbit of Io, the closest known moon of Jupiter at that time. The mean time interval between successive eclipses of Io by Jupiter is equal to its period of orbit, 42 h 28 min 42 s. However, for some months during the Earth year (region **A** in the Earth's orbit), the period of Io's orbit increased by a few seconds, whilst during other times (region **B** in the Earth's orbit) the period decreased.
It can be assumed that radius of Jupiter's orbit about the Sun is much larger than the Earth's.

a) Sketch a diagram of the orbits of the Earth (showing its direction of motion) and Jupiter to indicate where (**A** and **B)** these variations from the mean period would be greatest.

Diagram:

[2]

b) The radius of the Earth's circular orbit is 1.5×10^{11} m and its period can be taken as 365 days. If the variation of the period of the orbit of Io is up to 15 s longer or shorter than the mean, what value does this give for the speed of light?

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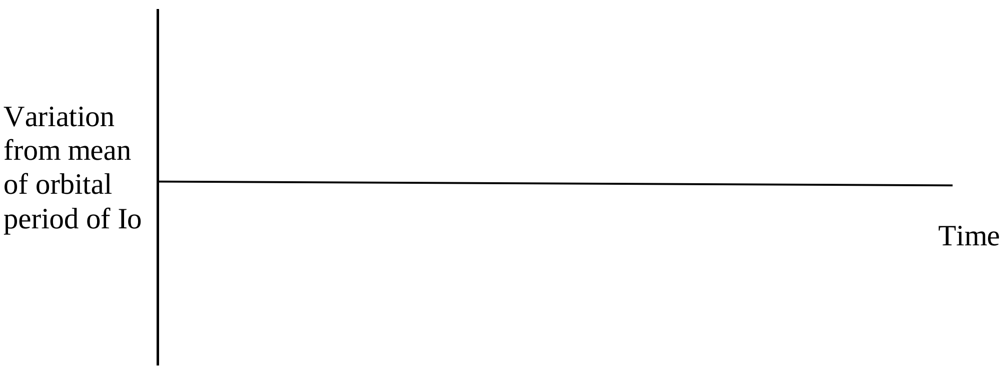
c) Sketch a graph on the axes showing the variation in the period of Io's orbit for one Earth year. Give values on the axes and mark on **A** and **B**.



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Question 12.

Resistors have a very important role to play in circuits and here are four examples in which the characteristics can be put to use.

a) In the circuit shown below with the arrangement of resistors R_1 and R_2, what is the ratio of $\frac{R_1}{R_2}$ so that the power dissipated in R_1 is equal to the power dissipated in one of the resistors R_2.

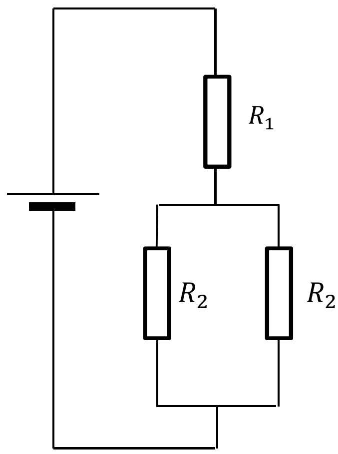

Figure 3. Simple arrangement of resistors with a cell.

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b) An analogue ammeter, with a moving coil and a needle on a scale, has a **f**ull **s**cale **d**eflection (f.s.d,. i.e. the needle has swung fully across the scale) when a current of 2.0 mA flows through the coil which has a resistance 5.0 Ω.

To measure a current of 0.20 A in a circuit, the ammeter would require a low value resistor to be connected in parallel so that not all the current flows through the coil. What is the value of the resistor needed?
Sketch a diagram to illustrate your approach.

Figure 4. Typical moving coil meter.

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c) If the 2.0 mA, 5.0 Ω moving coil meter is to be used as a voltmeter instead to measure 4.0 V f.s.d., what value series resistor would be used?

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A high gain amplifier is one in which the difference of the small input voltage between the two input leads is multiplied by a large factor and the polarity inverted (typically $\times\ -10^6$) i.e. $V_{out} = -10^6\, V_{in}$. This high gain is not very useful, and it is only approximate. The amplifier **A** shown in Figure 6 has two input and two output terminals, connected as shown. The polarity of E is opposite to that of C.

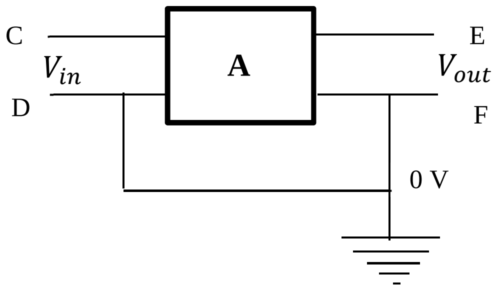

Figure 5. High gain amplifier for which $\mathbf{V_{in}} = -\frac{V_{out}}{10^6}$

d) In Figure 5, if $V_{out} = -2.0$ V, **mark clearly on Figure 5** the potentials of terminals C, D, E and F.

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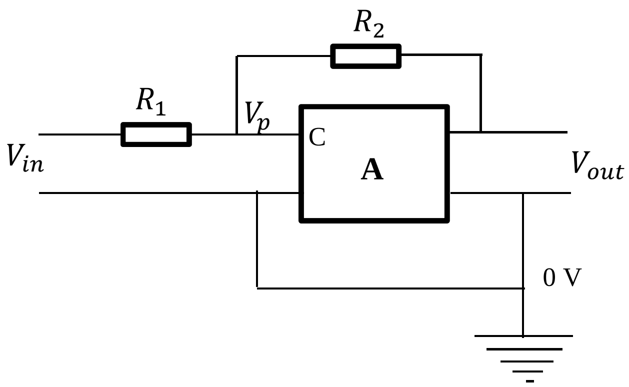

Figure 6. High gain amplifier with two resistors R_1 and R_2 attached.

Two resistors R_1 and R_2 are connected to the amplifier, as in Figure 6.
No current can flow in to terminal C on the amplifier.
The potential V_p at terminal C is very small i.e. $-V_{out}/10^6 = V_p$
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e) Write down the currents flowing through resistors R_1 and R_2 in terms of the polarities across them. What approximation can now be made in order to find a simple expression for the ratio of V_{out}/V_{in} , which is the gain of the amplifier when controlled by the resistors.

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Question 13.

The announcement in 2016 about the discovery of gravitational waves has demonstrated the effects that gravity has in more subtle ways than just dropping a weight on our toe. The *Einstein Tower gedanken (thought) experiment* illustrates that electromagnetic waves are affected by gravity. It uses the equation for the equivalence of mass and energy, $E = mc^2$ in which c is the speed of light, m is the mass of an object, and E is the amount of energy into which it can in principle be converted.

a) If a small mass m is dropped from a height h, it gains kinetic energy as it falls. On reaching the ground, it could all (in principle) be converted into electromagnetic waves in the form of photons (packets of energy), each of energy $E = hf$, and reflected back up. The photons could then be converted back into a mass. Explain using the concept of energy conservation, why this process indicates that photons must be affected by gravity.

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b) A photon of frequency of 4.2×10^{14} Hz is emitted towards the ground from a satellite orbiting the Earth at a height of 450 km. Assume that the acceleration due to gravity, g is constant and the motion of the satellite may be ignored in this calculation. By identifying the energy of the photon as it leaves the satellite with a fictitious mass m_γ, calculate the change in frequency, Δf, of the photon when it reaches the ground.

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c) When the photon travels the 450 km to Earth, how many wavelengths of light would this be if the photon was not affected by gravity?

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d) Since the photon is affected (slightly) by gravity, comment on how the wavelength changes as the photon falls.

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e) What is the change in the number of complete wavelengths along the 450 km path due to the effect of gravity on the photon?

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END OF PAPER

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