BPhO British Physics Olympiad

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BPhO Physics Challenge

September/October 2024

Instructions

Time: 1 hour.

Questions: Answer ALL questions.

Marks: Total of **50 marks**.

Instructions: You are allowed any standard exam board data/formula sheet.

Equipment: Any standard non-graphical calculator may be used.
Ruler and pencil may be needed.

Solutions: These questions are about problem solving. Draw diagrams in order to understand the questions. You must write down the questions in terms of symbols and equations; then try calculating quantities in order to work quickly towards a solution. In these questions you will need to explain your reasoning by showing clear working. Even if you cannot complete the question, show how you have started your thinking, with ideas and, generally, by drawing a diagram.

Clarity: Solutions must be written legibly and set out properly with a "narrative" which links one step to the next (and, so, therefore, hence, but, also, using equ 5, etc.).

Important Constants

Constant	Symbol	Value
Speed of light in free space	c	$3.00 \times 10^8\ \mathrm{m\,s^{-1}}$
Elementary charge	e	$1.60 \times 10^{-19}\ \mathrm{C}$
Mass of electron	m_e	$9.11 \times 10^{-31}\ \mathrm{kg}$
Atomic mass unit	u	$1.66 \times 10^{-27}\mathrm{kg}$
Earth's gravitational field strength	g	$9.81\ \mathrm{N\,kg^{-1}}$
Atmospheric pressure at the Earth's surface	P_0	$1.01 \times 10^5\ \mathrm{Pa}$
Radius of the Earth	R_E	$6.4 \times 10^6\ \mathrm{m}$
Planck constant	h	$6.63 \times 10^{-34}\ \mathrm{J\,s}$
Avogadro constant	N_A	$6.02 \times 10^{23}\ \mathrm{mol^{-1}}$

Qu 1. This question is about estimations.

Especially at the start of research or when solving a complex problem, it is useful to have an estimate of the sort of outcome to expect; making approximate calculations is a useful skill.
Use the information given and any other estimated values of your own to answer the following:

i) In ancient times Eratosthenes noted that the towns of Syene (now Aswan) and Alexandria lay $800\ \mathrm{km}$ apart along a meridian (line of longitude). When the Sun was overhead at Syene, the shadow cast by an obelisk at Alexandria indicated the elevation of the Sun to be $83°$ there. What might Eratosthenes have estimated as the radius of the Earth?

ii) On Earth, atmospheric pressure is approximately $100\ \mathrm{kPa}$ and the density of air is approximately $1.3\ \mathrm{kg\,m^{-3}}$. Estimate the height of the atmosphere that results from these figures. Hence estimate the number of molecules the atmosphere contains.
The relative atomic masses of nitrogen and oxygen atoms are 14 and 16 respectively.

iii) There is 3700 J of translational kinetic energy contained in a mole of argon gas of relative atomic mass 40, at room temperature. Estimate the average speed of the gas molecules.

[8 marks]

Qu 2. This question examines some aspects of superposition and the interference of light.

A so-called "air wedge" can be formed by placing together two microscope slides and separating them at one end with a sliver of tissue paper, as shown in **Figure 1,** (**NOT** to scale). When this arrangement is illuminated by monochromatic light, a fringe pattern is observed as shown in **Figure 2.**

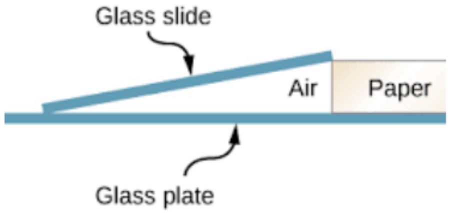

Figure 1: Schematic of air wedge

Figure 2: The fringe pattern that is observed

i) Explain the formation of equally spaced light and dark fringes (you may refer to **Figure 3,** if you find that helpful).

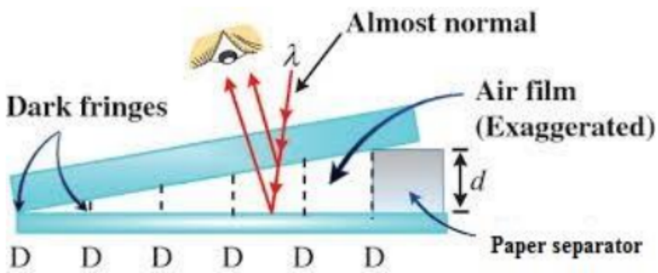

Figure 3: Schematic of air wedge with dark fringes shown

ii) Why is there a **dark** fringe indicated at the line of contact of the two glass plates when there is clearly zero path difference?

iii) Explain why the fringe pattern may be regarded as a contour map of the gap thickness and suggest in outline how this might assist in the study of the profile of nearly flat, reflective surfaces.

iv) When the wedge is illuminated with white light, coloured fringes are seen. These are **NOT** the familiar sequence of colours of the visible spectrum (ROYGBIV) but colours like those seen in bubbles and oil slicks. Explain why this is so.

[9 marks]

Qu 3. This question explores the consequences of symmetrical and asymmetrical vibrations.

a) **Figure 4,** shows a marble with its gravitational potential energy increased by moving it up a smoothly curved symmetrical slope.
You may assume that the slope has no friction, and that the marble slides and does not roll.

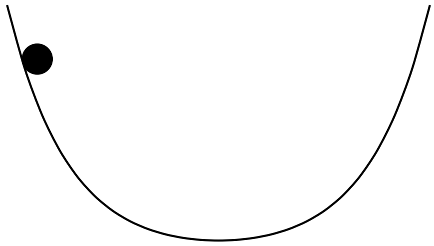

Figure 4: Smoothly curved **symmetrical** slope.

i) Describe the motion of the marble in terms of its position, speed and energy, once released.

ii) Stating any assumption you make, what is the maximum height to which the marble may rise at each extreme of its motion?

iii) Copy Figure 4 and show the extremes of motion of the marble for three different starting heights.

iv) Now mark the mid-points of the oscillations of the marble for each starting point. What do you notice about the mean position of the marble as the energy of the system is altered?

[6 marks]

b) **Figure 5,** shows a marble with its gravitational potential energy increased by moving it up a smoothly curved **asymmetrical** slope.

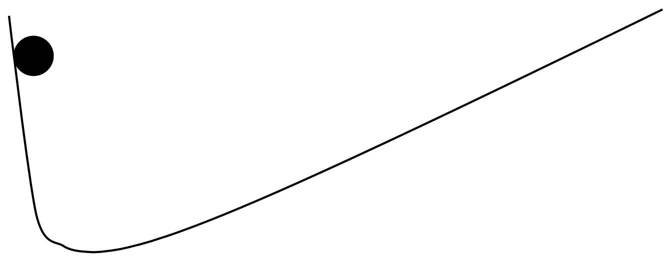

Figure 5: Smoothly curved **asymmetrical** slope.

Repeat the stages of argument in part (a) for this new situation.

[5 marks]

What you have now described is the behaviour of an anharmonic oscillator.

c) i) Sketch a graph of $y = \frac{1}{x}$ in the first quadrant.

ii) On the same axes, sketch the graph of $y = \frac{1}{x^2}$.

iii) Without further sketching or calculation, suggest how the curve representing $y = \dfrac{1}{x^n}$ alters, as n increases.

[3 marks]

Graphs of this sort provide a simplified model of an inter-atomic bond. For two atoms a distance r apart, their potential energy associated with inter-atomic attraction may be postulated as proportional to $-r^{-6}$. At the same time, when atoms approach closely enough, "contact" between them leads to a rapidly escalating repulsive force, leading to the idea of an effective "hard-core radius", or interpreting the atom as an almost rigid sphere when squeezing two of them together: the potential energy arising from this is postulated as proportional to $+r^{-12}$.

iv) On the same axes, sketch two curves representing the two potential energies associated with this model of inter-atomic bond energies.

v) Add to your graphs a third, bold line representing the total potential energy of the system (i.e. the sum of the two energies (curves) already on your graph.)

vi) Is the potential energy well that you have sketched symmetrical or asymmetrical?

vii) When a system is at equilibrium, what can you say about its potential energy? Hence mark **X** at the position on your bold curve representing the separation of the two atoms held together by a bond and in equilibrium.

viii) Now, imagine the bound pair of atoms to be heated: draw a horizontal line to show the level of potential energy in the bond and mark the extremes of its consequent vibration with * symbols. Hence indicate the mean separation of the atoms.

ix) Mark similarly the mean separation of atoms for two other differing levels of energy.

x) Hence, explain the phenomenon of thermal expansion.

[8 marks]

Qu 4. This question is about using symmetry to simply complicated circuits.

Symmetry is a useful tool in simplifying otherwise complex problems. For each of the networks illustrated below, find the effective resistance between the points **A** and **B** (for which task, considerations of symmetry will be very helpful!)

a) ABCD is a hollow tetrahedron consisting of five wires each of resistance 30 Ω, and one variable resistor at CD, of resistance R, as shown in **Figure 6.**

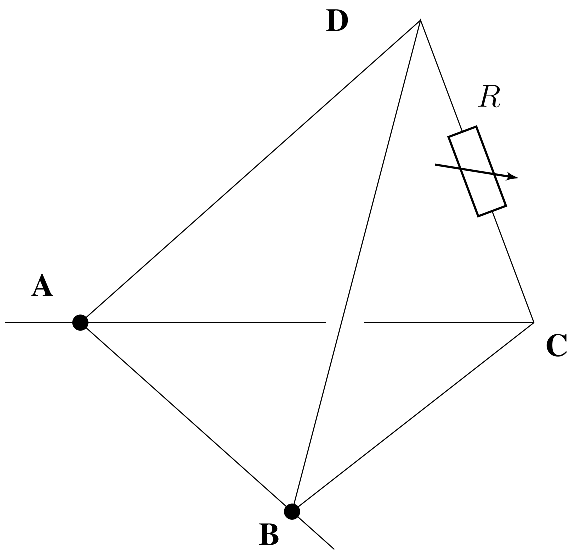

Figure 6: Tetrahedral arrangement of wires containing variable resistor R.

[3 marks]

b) All resistors are of value 30 Ω and are arranged as shown in **Figure 7.**

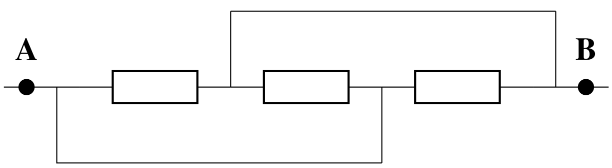

Figure 7: Three 30 Ω resistors

[2 marks]

c) All resistors are of value 30 Ω and are arranged as shown in **Figure 8.**

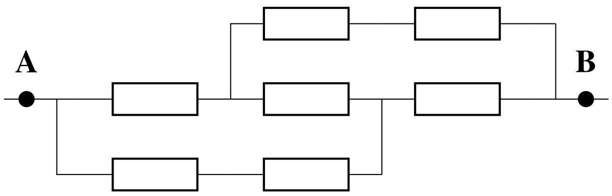

Figure 8: Seven 30 Ω resistors

[6 marks]

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