BPhO
British Physics Olympiad

BPhO Physics Challenge

(formerly A2 Challenge)

September/October 2019

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	$1.60 \times 10^{-19}\,\mathrm{C}$
Acceleration of free fall at Earth's surface	g	$9.81\,\mathrm{m\,s^{-2}}$
Planck constant	h	$6.63 \times 10^{-34}\,\mathrm{J\,s}$
Avogadro constant	N_{A}	$6.02 \times 10^{23}\,\mathrm{mol^{-1}}$
Molar Gas constant	R	$8.31\,\mathrm{J\,mol^{-1}\,K^{-1}}$
Density of water	ρ_w	$1000\,\mathrm{kg\,m^{-3}}$

Qu 1. This question examines some aspects of balanced forces. Answers may include a sketch and a description.

a) State **two** conditions necessary for the equilibrium of a body.

[1]

There are three classes of equilibrium, which can be exemplified by a cone resting on a horizontal surface as in **Figure 1**:

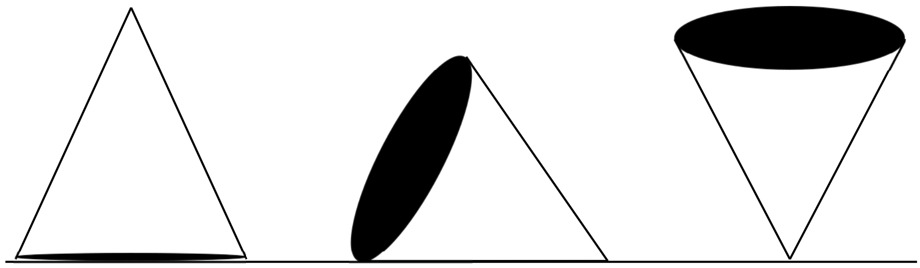

Figure 1

b) (i) When the cone on the left is tilted slightly from the position shown, what happens to the height of its centre of mass and to its gravitational potential energy?

(ii) The left-hand cone is plainly stable. Use the concept of moments to explain why this cone is stable against small displacements.

(iii) Now apply your arguments to explain why the cone on the right is in unstable equilibrium.

(iv) The middle cone, resting on its curved surface, is said to be in neutral equilibrium. Justify this description by considering the gravitational potential energy of this cone when displaced by rolling sideways.

[5]

c) (i) Draw a diagram of forces, to show two non-zero forces of **equal magnitude**, which are acting on a rigid body in equilibrium.

(ii) Now, consider three such forces of equal magnitude acting on the body. How must they be arranged for equilibrium?

(iii) Now, consider four such forces of equal magnitude acting on the rigid body. Show one way in which they may be arranged for equilibrium,

a. if they are co-planar
b. if they are not co-planar

[7]

[13 marks]

Qu 2. This question looks at some simplified design considerations for a domestic electrical supply system.

a) (i) A fuse is a safety device commonly inserted into domestic electrical circuits: against what fault does it protect?

(ii) Why is this fault a particularly dangerous hazard?

[2]

b) An electrical engineer intends to install a supply in a garage some distance from his house where there is a $230\,\mathrm{V}$ (AC) supply. He uses $50\,\mathrm{m}$ cable with two copper current-carrying conductors, for live and neutral, of cross-sectional area $2.5\,\mathrm{mm}^2$, which are nominally safe to carry a current of $20\,\mathrm{A}$.

(i) What is the total resistance of the current-carrying conductors in this length of cable? (Resistivity of copper is $1.7 \times 10^{-8}\,\Omega\,\mathrm{m}$)

(ii) Hence determine the potential difference available at the garage when a current of $20\,\mathrm{A}$ is being delivered there.

[3]

c) Apprentice electricians are expected to be familiar with the *adiabatic calculation for cable size*. We will look at a simplified version of this idea as applied to the garage supply described above.

Suppose that a fault arises in the garage, which accidentally joins the ends of the two conductors of the cable together.

(i) What current now flows in the cables?

(ii) Modern electrical systems have safety devices which disconnect the supply completely within approximately $100\,\mathrm{ms}$ when any one of a number of faults occurs. During this interval it is assumed that no heat escapes from the cables (this is the meaning of *adiabatic*).

Calculate the rise in the temperature of the cables during the disconnection period. (Specific heat capacity of copper is $385\,\mathrm{J\,kg^{-1}K^{-1}}$; density of copper is $8940\,\mathrm{kg\,m^{-3}}$)

(iii) This clearly complies with a design criterion that the temperature rise should not exceed $100\,\mathrm{K}$. However, this situation may alter if the length of the cable were different: suggest qualitatively how the result might be affected by a shorter cable.

[7]

[12 marks]

Qu 3. This question relates to a number of phenomena associated with refraction of light.

a) The refractive index of glass with respect to air is 1.52.

(i) Calculate the critical angle for glass in air.

(ii) Copy the three diagrams in **Figures 2a, b** and **c** and, using your answer for part (i) above, complete the paths of the light rays through each prism shown. (**O** and **X** are used in part (iii).)

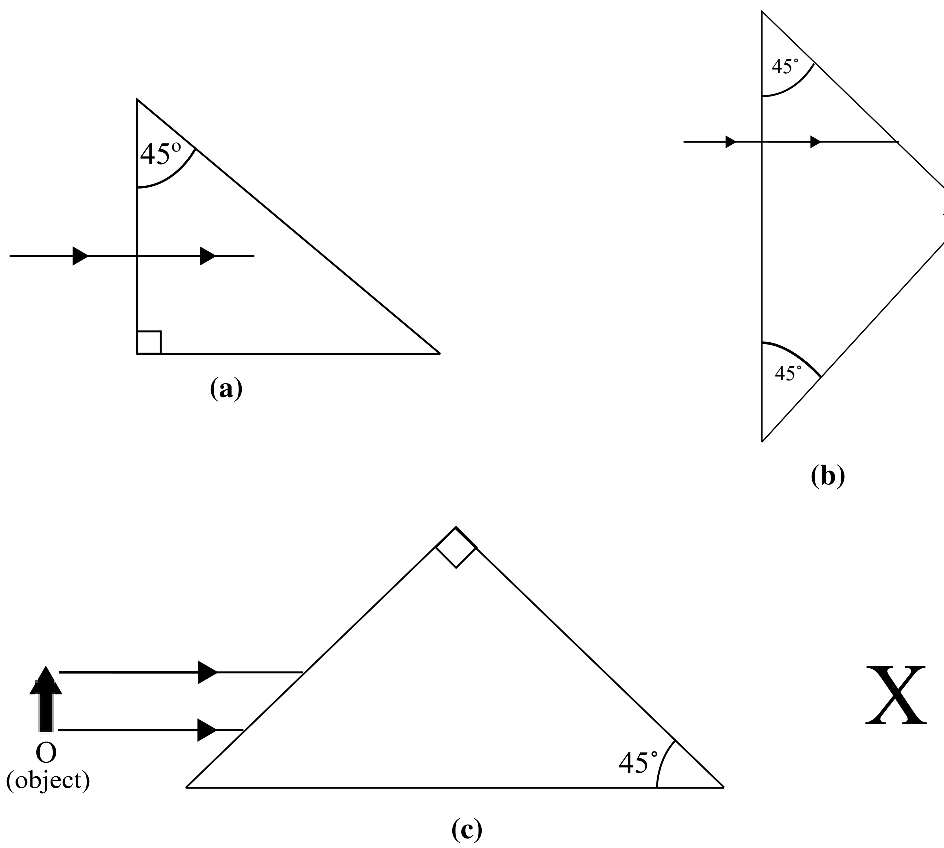

Figure 2: Paths of light through prisms

(iii) In **Figure 2c**, what would on observer at **X** notice about the image of the object **O** which is shown ?

[4]

b) (i) Copy **Figure 3** and complete the path of the light ray through the glass prism. The ray enters and emerges on the two sides adjacent to angle A.

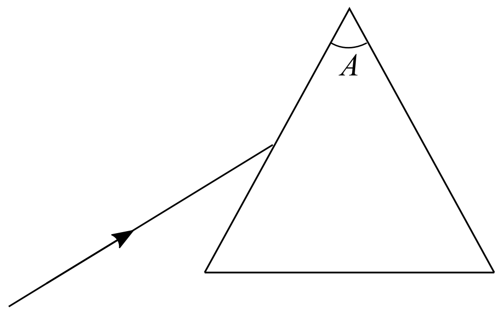

Figure 3

Extend the incident ray forwards, and then the emergent ray backwards to meet the incident ray. The acute angle between these rays is the *angle of deviation*: mark this angle D. Also mark the angles of incidence outside and inside the glass I and i respectively, and the angles of refraction inside and outside the glass r and R respectively (so the order of the angles from left to right is I, r, i, R).

(ii) Show that

$$i + r = A$$

and use this result to show that:

$$D = I + R - A$$

(iii) Show that for a ray passing symmetrically through the prism that

$$I = \frac{1}{2}(A + D)$$

In the same situation, show that the angle of refraction, r, at the left hand face is given by

$$r = \frac{1}{2}A$$

and that therefore the refractive index of the material of the prism is given by

$$\frac{\sin \frac{1}{2}(A + D)}{\sin \frac{1}{2}A}$$

(iv) An equilateral prism is made from glass with a refractive index of 1.62 at $400\,\mathrm{nm}$ and 1.59 at $700\,\mathrm{nm}$. Using the result above,

(a) Calculate the values of the angle of deviation for the two wavelengths and the difference between them.
(b) **Name the colour** which is deviated by the larger angle.

[8]

[12 marks]

Qu 4. This question is about ideal and real gases.

a) Many common gases behave in a manner which approximates well to ideal gas behaviour at usual temperatures and pressures.

(i) In contrast to an ideal gas, the molecules of a real gas attract each other when separated: as the temperature of a gas is lowered, what non-ideal behaviour will be observed as a consequence of inter-molecular attraction?

(ii) An alternative aspect is that the molecules of an ideal gas are supposed to occupy negligible volume. How would the behaviour of a real gas differ from that of an ideal gas, held at constant pressure, if it were possible to reduce the temperature of each to absolute zero? (*Note that this is a **hypothetical** suggestion, as the third law of thermodynamics precludes accessing absolute zero*)

[3]

b) State the meaning of the symbols in the equation of state for an ideal gas, which is:

$$pV = nRT$$

[1]

c) A fine, uniform tube is closed at one end and a sample of gas trapped in it by a thread of mercury of length $7.6\,\mathrm{cm}$, as in **Figure 4**. The tube may be held vertical with the closed end either at the top or bottom, as shown (you may assume that the tube is sufficiently long so that you can neglect the curvature of the closed end, and that its contents cannot fall out of the end). The temperature of the gas remains constant.

With the sealed end uppermost, the length of trapped air is $77\,\mathrm{cm}$. When the tube is inverted, this length decreases to $63\,\mathrm{cm}$. Use this information to determine atmospheric pressure. (You may assume that a $7.6\,\mathrm{cm}$ thread of mercury exerts a pressure of $10\,\mathrm{kPa}$)

[4]

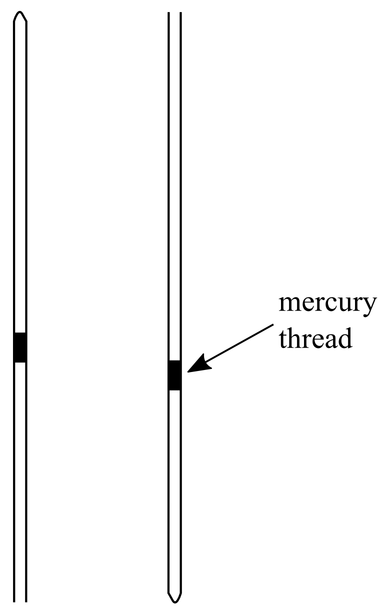

Figure 4

d) A sample of an ideal gas is contained in a vessel comprising two unequal bulbs joined by a tube of negligible volume. The larger bulb has volume $1.0 \times 10^{-2}\,\mathrm{m}^3$ while the smaller bulb has volume $1.0 \times 10^{-3}\,\mathrm{m}^3$. The gas in the vessel has a temperature of $27\,^{\circ}\mathrm{C}$ and an absolute pressure of $100\,\mathrm{kPa}$.

(i) Calculate the number of moles of gas in the vessel.

(ii) The smaller bulb is now immersed in a water bath at $77\,^{\circ}\mathrm{C}$ while the larger one remains at $27\,^{\circ}\mathrm{C}$. The vessel is then allowed to come to equilibrium, so that no more gas flows through the tube. Calculate the new pressure in the system.

[5]

[13 marks]

END OF PAPER

BPhO Sponsors

Worshipful Company of Scientific Instrument Makers