BPhO
British Physics Olympiad

BPhO Physics Challenge
September/October 2021

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.
Graph paper.

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	$9.81\,\mathrm{N\,kg^{-1}}$
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	$8.31\,\mathrm{J\,mol^{-1}\,K^{-1}}$

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 suggestions given and any other estimated values of your own to answer the following:

a) What is the equivalent mass of a joule?

[2]

b) Many atomic processes take (within an order of magnitude) about a nanosecond. By considering emission of a photon from an excited atom, calculate the approximate size of a photon. (This is actually a much more complex problem than this simple approach would suggest).
How many wavelengths of visible light does this correspond to?
For visble light $\lambda \approx 600\,\mathrm{nm}$

[3]

c) An inventor designs a novel type of battery reputed to have an emf of $2\,\mathrm{V}$ and an internal resistance of $1\,\mu\Omega$. He claims that this device could deliver $1\,\mathrm{MW}$ to an appropriate load. Comment on the feasibility of this and any safety considerations in the employment of such a power source.

[4]

[9 marks]

Qu 2. This question is about stopping distances for motor vehicles.

Many of the students participating in this Physics Challenge in the UK will also be learning to drive. So, the extract from the Highway Code reproduced below in **Fig. 1** may well be familiar to those who have worked for the theory test.
We will explore the physics of this table together with some associated phenomena.

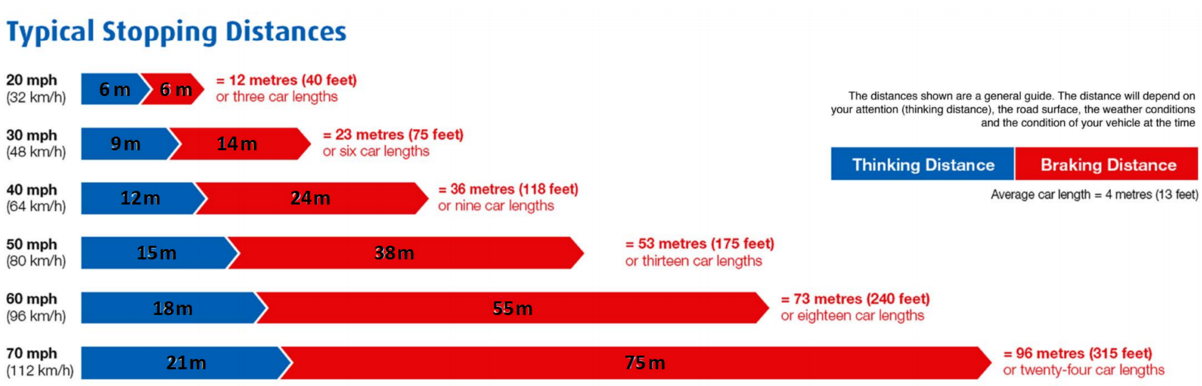

Figure 1: A table of stopping distances taken from the Highway Code.
credit: https://assets.publishing.service.gov.uk/media/559afb11ed915d1595000017/the-highway-code-typical-stopping-distances.pdf

a) (i) What is the kinetic energy of a car of mass $1000\,\text{kg}$ travelling at $30\,\mathrm{m\,s^{-1}}$? [2]

(ii) A car travelling at approximately $30\,\mathrm{m\,s^{-1}}$ in the country is required by law to halve its speed on entering a built-up area. What fraction of its kinetic energy is lost in doing this? [2]

b) (i) By inspection of the values given in **Fig. 1**, suggest a relationship between the thinking distance, T, and the speed, v. [1]

(ii) The Thinking Distance in the table derives from empirical information about the behaviour of drivers. If you were to propose a theoretical explanation of this phenomenon, what assumption would be needed to explain your suggested relationship? [1]

c) (i) Clearly, the speed and stopping distance have a different relationship. A student who has seen part (a) of this question suggests that the braking distance, B, is proportional to the square of the speed, v^2.
Using the data, devise a test to check this hypothesis and comment on the results of your test.
[3]

(ii) Again, the observed relationship is only an empirical finding. If you were to devise a theoretical explanation of the $B \propto v^2$ relationship, what assumption would you need to make about the braking behaviour of a car?
[1]

(iii) Calculate the deceleration of a car when it brakes from a speed of $80\,\mathrm{km\,h^{-1}}$.
[3]

(iv) Hence determine the (minimum) coefficient of (static) friction, μ, for contact between car tyres and the road. (μ is the ratio of the maximum braking force, before skidding sets in, to the weight of the car). [2]

(v) It is often stated (incorrectly) that the value of μ cannot exceed unity. But, if tyres had this excellent level of grip, what would be the minimum stopping distance from $96\,\mathrm{km\,h^{-1}}$?
[2]

[17 marks]

Qu 3. This question is about reflection of waves.

The diagram below, **Figure 2**, shows the effect of touching the centre of the surface of water in a glass.

Figure 2: Surface of water in a glass disturbed by touching by a finger.

a) Draw a series of four sketches to show the motion of a single circular ripple, viewed from above, from the time it is generated at the centre to the time it returns to the centre. Include arrows to show the direction of the ripple. [2]

b) Explain why the amplitude of the ripple reduces as the ripple travels outwards and its radius increases. [1]

This situation is analogous to the focussing effect of a circular mirror. Here the object is the initial contact with the water and the (real) image is at the final point of convergence of the ripple.

Another, familiar situation in which image distance equals object distance is shown in **Fig. 3**. (The lens is assumed to be thin for the purpose of drawing rays)

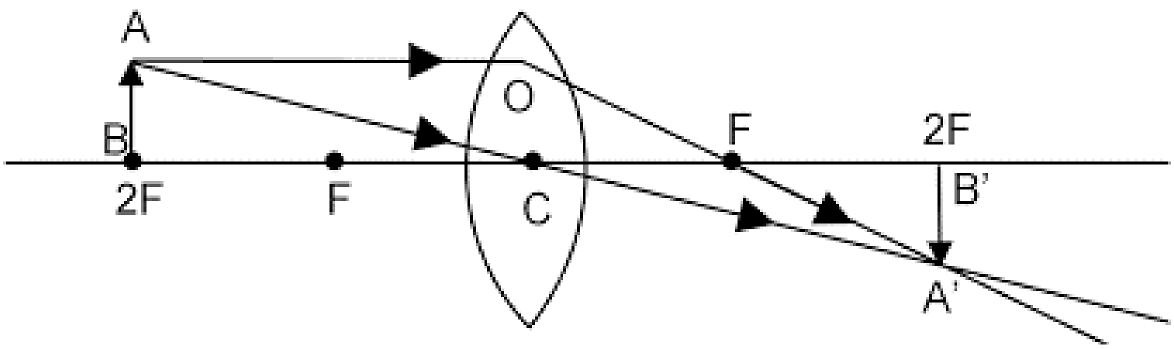

Figure 3: Ray diagram for a thin converging lens.

c) Explain how this lens behaviour resembles the reflecting behaviour of a circular mirror and use your explanation to state the relationship between the focal length of a mirror and its radius of curvature. [2]

Figure 4: A caustic curve shown by the light reflected off the curved side of a mug.

The symmetry of **Fig. 2** ensures that the focussing in that instance is precise. When the object is at a different distance, precise focussing does not happen: you may have observed for yourself the "caustic curve" as illustrated in **Fig. 4** by the bright white curve on the right side of the mug. A better focussing geometry is given by a parabolic mirror.
The standard equation of a parabola is

$$y^2 = 4ax$$

where a is the so-called focal distance of the parabola.

d) Sketch a graph of the function $y^2 = 4ax$. This must occupy at least half a page.
Add to your sketch a light ray parallel to the $x-$axis, meeting the parabola at the general point (X, Y). [2]

e) Show mathematically that this arbitrary ray is reflected through the point $(a, 0)$ and so justify describing a as the focal distance. [6]

You may find the identity $\tan(2\theta) = \dfrac{2\tan\theta}{(1 - \tan^2\theta)}$ useful.

[13 marks]

Qu 4. This question relates to some ideas about a novel material called graphene which may become important in a future technology.

a) What is meant by the prefix nano ? [1]

b) State the size of a typical atom in nanometres. [1]

You will be familiar with the giant molecular structure of graphite from your chemistry lessons. It is made of layers of carbon atoms, each with the atoms arranged as a hexagonal grid, as in **Fig. 5**, within which there are both strong covalent bonds and delocalised electrons (for chemists only: in the $\sigma-$bond framework and the $\pi-$bonding network) which account for the conducting properties of graphite. The weaker bonding between such layers accounts for the lubricating properties of graphite.

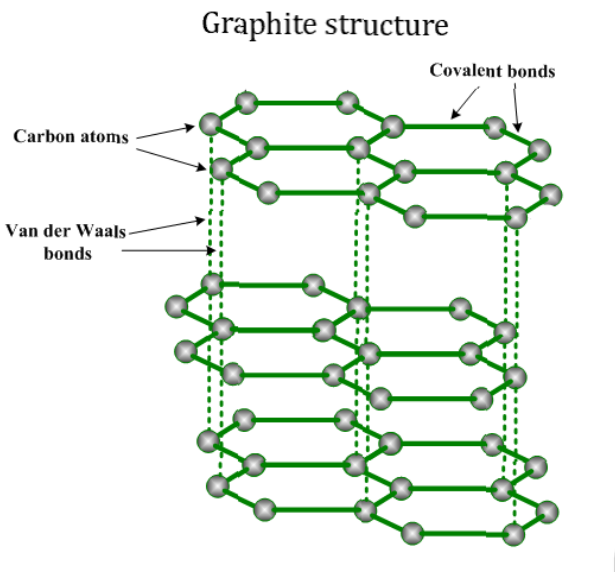

Figure 5: The layered hexagonal structure of graphite.
credit: https://www.substech.com/dokuwiki/doku.php?id=graphite

One single layer from this structure is graphene. Graphene layers can also be formed into hollow balls, tubes and other configurations.

c) Suggest why such balls, tubes etc are often referred to as nanomaterials. [1]

We are only just beginning to discover the many diverse uses of nanomaterials.

In the future, as the miniaturisation of microprocessors continues, an obvious limit to the technology is when the size of one active unit in a device approaches the size of an atom. We will explore, speculatively, an aspect of passing a current into and out of the structure of graphene.

Fig. 6 represents part of an infinite graphene layer for which we wish to find the measured resistance between a pair of atoms located at points **A** and **B**. Each straight line (bond) between two nodes represents a resistance R.

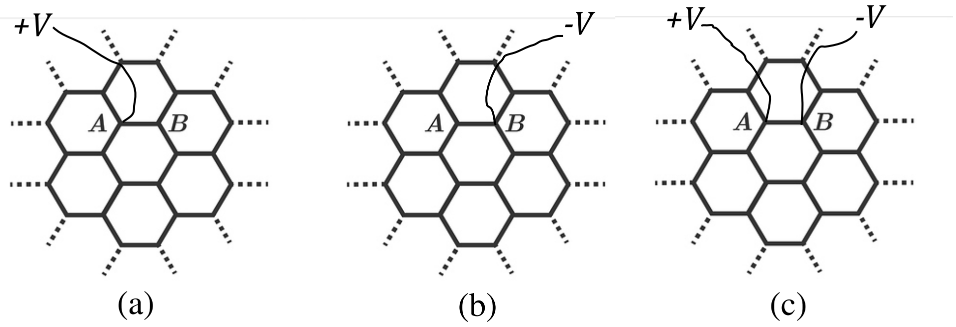

Figure 6: The single layer hexagonal structure of graphene.

d) Considering for the moment **Fig. 6(a)** in which an external wire at potential V is attached to **A**, so that a current I flows into **A**, and then flows out into the wider network, eventually being dissipated to ∞ where the potential is zero. State the values of the three currents flowing away from **A** in terms of I. Make a statement to justify your assertion. [2]

e) Now consider **instead** an external wire at potential $-V$ attached to **B** as in **Fig. 6(b)**, so that a current I flows out from the network into the wire, flowing from infinity where the potential is zero. State the values of the three currents flowing towards **B** in the network. [1]

f) Now a current I flows through the contact wires connected so that I flows in at **A** and out at **B**, as in **Fig. 6(c)**. The *principle of [linear] superposition* (which will be more familiar to you in your studies of the interference of waves) can also be applied to the currents you have postulated. State the total current through the bond **AB**. [1]

g) Now, with current I flowing into the network at **A** and the same current flowing out of the network at **B**, state the current flowing from **A** to **B** by all other routes through the infinite network (i.e. not through resistor **AB**). [1]

Now, we can represent this scenario much more simply. Suppose that the bond **AB** has resistance R and that that the remainder of the network can be replaced by a single resistor R'.

h) Draw the combination of R and R' conected between **A** and **B**, then add to your diagram the currents you have calculated in parts (f) and (g) above. [1]

i) Hence or otherwise, determine the value of R' in terms of R. [1]

j) Therefore, in terms of R, the resistance of a single bond **AB**, what is the effective resistance between **A** and **B**; i.e. for a current I, entering through a single contact point at **A** and flowing through the infinite structure, so that the same current I is extracted from a single contact point at **B**? [1]

[11 marks]

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