Physics Questions

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Read This Carefully:

This document lists the questions I have sent in the group. The document will be updated once per day, and hopefully the answers (if I have time) will be updated per day as well. Please do not share the document without my permission.
Here are some disclaimers:

1. This document is for academic use only. Please DO NOT SHARE with anyone (even for fun or to show off). Otherwise little Lucas would be really mad.
2. I am a training physicist and like goldfish, have little memory about what I have done in the past (which means the HKDSE). Generally the questions will be conceptually funny and challenging for HKDSE. I will use some terms that you may not understand. If that is the case, send me an email and try and check if I am still sane.
3. There are inevitably some solutions where I would use some terms you will definitely not seen before. That is for enthusiasts (and partly because I want to show off).
4. Please discuss in the group. A wrong answer is better than a nil answer (even in the HKDSE). It helps me identify which concepts in particular people are struggling with.
5. Send me HAHAs if you like what I am doing. Send MAD if you don't like it.
6. Any suggestions are helpful. Please email me at tyl40@cam.ac.uk or just shout in the group.

Daily Questions

Question 1.1

Define the electric potential. How does it differ from the electric field? (Hint: Can I increase the potential of the entire system by an arbitrary amount? How about the electric field?) What is the difference between EMF and voltage? (24 Feb)

Solution:

This is a conceptual question. The key term I want to talk about is *potential.* First the definitions should be from your notes. Here I am giving your an alternative definition using my own wordings.

Definition 1. *The electric field* $\mathbf{E}$ *is defined as*

$$\mathbf{F} = q\mathbf{E} \tag{1}$$

where $\mathbf{F}$ *is the electric force experienced by the test charge.*

i. e. This means that the electric field is the force per unit charge. For the electric potential, it is slightly different:

Definition. *The electric potential* V *is the work done per unit charge against the electric field.*

Basically you can think of potential as the amount of tendency you have to push some charge down the electric field. An analogue is a water fountain and a pump - you can pump the water to a higher height and it has a tendency to flow down a pipe which leads water from a higher altitude to a lower one. Note that there is no numbering - this is not a formal definition. For enthusiasts, read the following definition.

Definition 2. *The electric potential* V *is a scalar field defined as the work done against field when moving unit positive charge from* A *to* B*:*

$$V = -\int_A^B \mathbf{E} \cdot d\mathbf{s} \tag{2}$$

Note that there is a minus sign. It comes from the fact that work is done against the field.

From these definitions you will have your usual equations of single charges (known as monopoles), which follows from Coulomb's Law.

Example 1. *The electric field for a monopole charge* Q *distance* r *away is*

$$\mathbf{E} = \frac{1}{4\pi\epsilon_0}\frac{Q}{r^2}\mathbf{e_r} \tag{3}$$

where $\mathbf{e_r}$ *is the unit radial vector. The corresponding potential* V *is*

$$V = \frac{1}{4\pi\epsilon_0}\frac{Q}{r} \tag{4}$$

The key here is that the potential is defined to an arbitrary constant. This means that we can shift the potential of the entire system by constant C and it makes no change to our physical model. The potential is only helpful if we compare two points, i. e. the potential difference ΔV between two points. The real physical quantity that can be measured, per se, is the electric field $\mathbf{E}$, not the potential V.

Remark. *I have said that potential something physical. Yet we can measure the potential in a circuit. This is because when we measure potential using a voltmeter we arbitrary (which you may not know) pick a point and set it to* 0. *Usually the instrument displays the potential difference, since absolute potential is not a useful physical concept at all.*

Remark. *It is a convention to set the potential at infinity to* 0.

What is the electromotive force then? Generally you will only see this concept in an electromagnetic induction context. In this context, the following definition applies.

Definition 3. *The electromotive force ε is defined as the closed loop work transferred to a unit charge as it transverse once around the loop. This is mathematically defined as the closed loop integral:*

$$\varepsilon = \oint \mathbf{E} \cdot d\mathbf{l} \tag{5}$$

This is not a concept required in DSE. In fact we only cover that last term so if the above discussion confuses you just note that the two terms approximately mean the same thing.

Remark. *In fact, if you compare this to the bookwork definition, which is the energy imparted by the source per unit charge passing through the voltage source, you should note that this is equivalent to the definition above - the electromotive force is generated from the generator, which requires electromagnetic induction.*

Question 1.2

We often see planets orbiting around something (usually a star). Does the star do work on the planet? Why? (25 Feb)

Solution:

This question is a simple mechanics conceptual question. You should first recall the definition of work done.

Definition 4. *The work done of a force on an object moved by a displacement* $d\mathbf{r}$ *is*

$$dW = \mathbf{F} \cdot d\mathbf{x} \tag{6}$$

Notice that this is a dot product i.e. you should recall that

$$\mathbf{A} \cdot \mathbf{B} = \mid \mathbf{A} \mid\mid \mathbf{B} \mid \cos\theta$$

where θ is the angle in between the two vectors. Now in a circular central force problem (i. e. a problem with force in the radial direction), the small incremental displacements are always perpendicular to the force. Therefore since $\theta = \frac{\pi}{2}$, we have $W = 0$. Hence the work done is always zero.

Remark. *This is essentially why the energy in a central force orbit is not affected by the central force (i. e. conserved)!*

Remark. *For an elliptical orbit the work done manifests itself as the potential energy change in the orbit. The net potential energy change in each complete revolution is* 0.

Question 1.3

Consider a horizontal set-up with a U-shaped metal tube (aka youtube) and a metal bar lying horizontally on the top of the parallel end of the tube such that the ends are orthogonal to the end of the U tube (the rod is far away from the curvy part). Apply a magnetic field $\mathbf{B}$ vertically downwards. Answer the following questions:

(a) Draw a diagram of the set-up as described above.

(b) Suppose the length between the parallel ends of the U tube is l. The resistance of the U tube is R, while the bar is a perfect conductor. What happens when I push the bar inwards with velocity v? Calculate the current.

(c) Now suppose I add a voltage source at the end of the tube. Draw the set-up again. Describes what happens to the rod. (26 Feb)

Solution:

I am not going to draw the diagram because it takes a really long time for me to computationally design something "nice". We will proceed with the question. I will introduce here a different definition (and some preliminary derivation that you might not have seen before) of the generated e. m. f. (compare this with Definition 5):

Definition 5. *The electromotive force generated is the work done per charge gained by the charge after passing through the loop once. Denoting the force per charge due to magnetic force as*

$$\mathbf{f} = \mathbf{v} \wedge \mathbf{B}$$

then the electromotive force ε is

$$\varepsilon = \int \mathbf{f} \cdot d\mathbf{r} \tag{7}$$

where $d\mathbf{r}$ is the infinitesimal displacement.

Here everything is nicely orthogonal to each other and we can hence write

$$\varepsilon = vBl \tag{8}$$

where l is the length of the wire. Using Ohm's Law the current through the system is hence:

$$I = \frac{\varepsilon}{R} = \frac{vBl}{R}$$

where R is the resistance of the wire. Alternatively one can recall Faraday's Law of Induction:

Law 1. *The Faraday-Lenz's Law states that when a magnetic flux Φ in a circuit changes, an electromotive force ε is induced where it is proportional to the rate of flux change. This is encapsulated in the equation:*

$$\varepsilon = -\frac{d\Phi}{dt} \tag{9}$$

Let x be the position of the rod from the tip of the U tube. The magnetic flux through the system is

$$\Phi = xBl$$

Differentiating both sides (dividing both sides) by t gives

$$\varepsilon = \mid -vBl \mid$$

where I have taken to absolute value to get the magnitude of the emf. Proceed with equation 8.

Remark. *Equation 7 is not explained well. Here I have included a derivation.*

Definition 6. *The Lorentz Force on a particle under an electric field* $\mathbf{E}$ *and a magnetic field* $\mathbf{B}$ *is given by*

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \wedge \mathbf{B}) \tag{10}$$

Assume we have a metal conductor in the shape of a wire which carries charges that are free to move within the wire. Suppose we move the wire with velocity $\mathbf{v}$ in a magnetic field $\mathbf{B}$. Let say the relative velocity of the free charges is $\mathbf{u}$ relative to the conductor. In the inertial frame of the observer the force on the charge is

$$\mathbf{F} = q(\mathbf{u} + \mathbf{v}) \wedge \mathbf{B}$$

Since the cross section dimensions of the wire is negligible the velocity $\mathbf{u}$ is parallel to the infinitesimal displacement of the charges $d\mathbf{r}$. Hence the work done per charge,

$$d\varepsilon = (\mathbf{u} + \mathbf{v}) \wedge \mathbf{B} \cdot d\mathbf{r}$$

reduces to

$$d\varepsilon = (\mathbf{u} \wedge \mathbf{B}) \cdot d\mathbf{r}$$

which is the differential form of equation 7.

Question 1.4

(Modified from IB Quantum Physics Example Sheet 1 Question 1, University of Cambridge.) An experiment on the photoelectric effect is carried out. A clean sodium surface is irradiated by light of a varying wavelength λ. The emitted electrons is subjected to the application of a voltage V such that the electrons are slowed down as it approaches the anode. The electron current is determined by an electrometer, in which the deflection d is proportional to the photoelectric current I_p. The results of the experiment is as follows. (27 Feb)

$\lambda = 546$(nm)		434		405		365		313	
V(V)	d (mm)	V	d	V	d	V	d	V	d
0.253	28	0.829	44	0.934	82	1.353	67.5	1.929	52
0.305	14	0.881	20	0.986	55	1.405	36	1.981	29
0.358	7	0.934	10	1.039	36	1.458	19	2.034	12
0.410	3	0.986	4	1.091	24	1.510	11	2.086	5
				1.143	3	1.562	4	2.138	2.5

From the results, try and estimate the stopping potential V_s for each wavelength of light. Hence deduce the Planck's constant $\hbar$ and work function of sodium W_{Na}.

Solution:

This is a question mainly on experimental methods, but you should be able to obtain the answers using the information provided and the knowledge from school. We know that the photocurrent and the voltage applied obeys the following relationship:

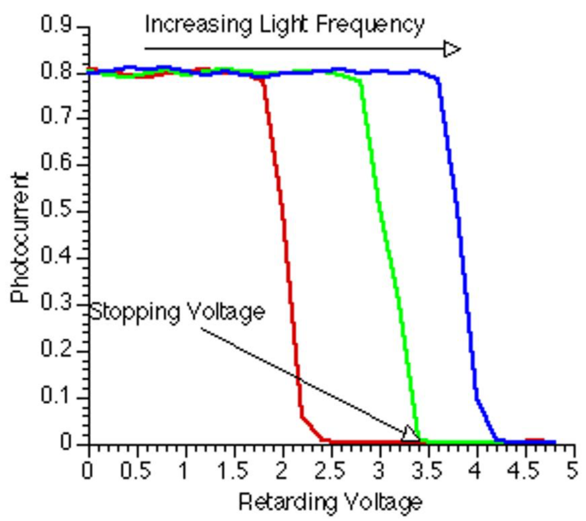

Figure 1: The plot shows the relationship between the photocurrent and the *retarding voltage*. *Retarding voltage* here is defined as the voltage applied to decelerate the electrons emitted from the cathode, retarding being that it slows down the electrons. The plot shows that light with different frequency causes a different stopping voltage.

To first approximation, the shape of the graph locally around the stopping voltage is linear. Hence by picking out the two smallest points of each set of data, one can generate a line which has an x-intercept, here being the stopping voltage for each wavelength of light. To calculate the work function and the value of $\hbar$, note that by energy conservation we have:

$$eV_s = h\nu - W_{Na} \tag{11}$$

e here being the electron charge (no negative sign). Using $c = \nu\lambda$ and $h = 2\pi\hbar$, rearranging Equation 11 gives:

$$V_s = \frac{2\pi c\hbar}{\lambda e} - \frac{W_{Na}}{e} \tag{12}$$

Hence plot a graph of stopping voltage V_s against the inverse of wavelength of light $\frac{1}{\lambda}$ would yield a linear curve (you can use linear regression, but a best-fit line also works here) with slope $\frac{2\pi c\hbar}{e}$ and an intercept of $-\frac{W_{Na}}{e}$. The values of the required constants can then be found.

Question 1.5

Calculate the effective resistance between points A and B of the following circuits. Assume that all of the resistors have a resistance of R (you can use 10Ω). (28 Feb)

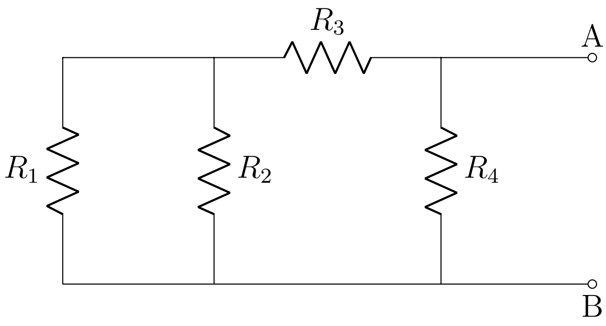

Figure 2: Circuit for Question 1.5(a).

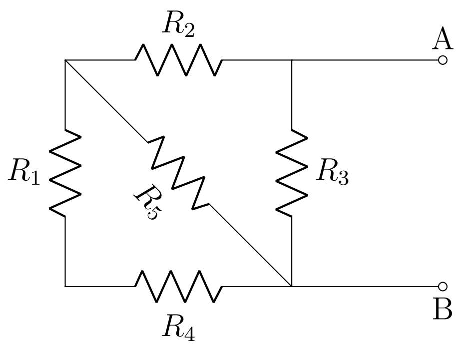

Figure 3: Circuit for Question 1.5(b).

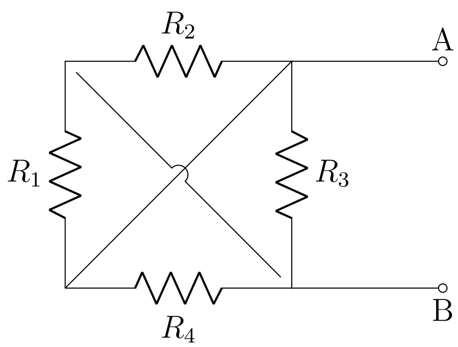

Figure 4: Circuit for Question 1.5(c). Ignore the disconnection of the jump crossing - it is due to a packaging issue and I will fix it in a later update.

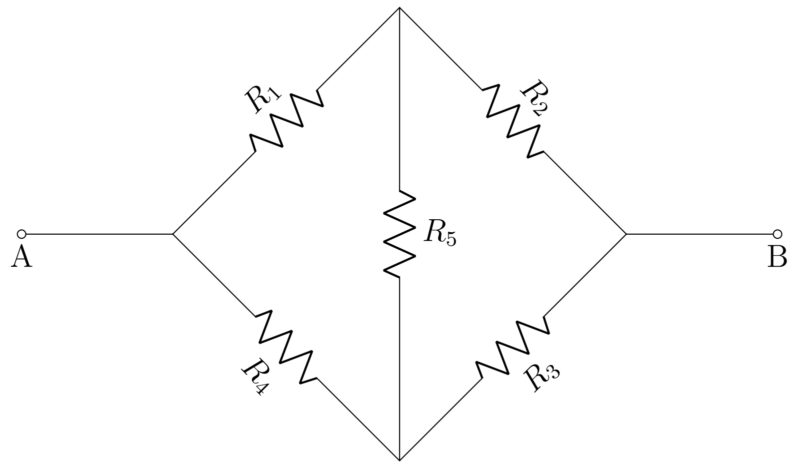

Figure 5: Circuit for Question 1.5(d).

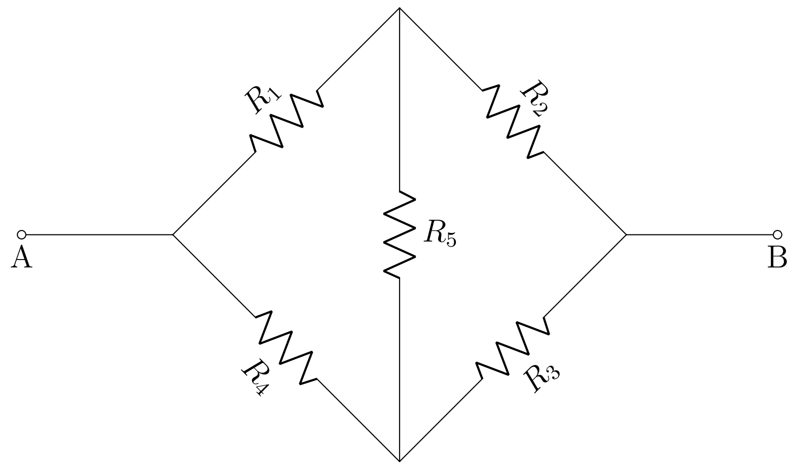

Figure 6: Circuit for Question 1.5(e). Here $R_1 = 2R$ and $R_2 = R_3 = R_4 = R_5 = R$. It is sufficient to just discuss how you would approach this problem without a detailed mathematical calculation.

Solution:

The key here is the rearrange the circuit such that you can spot the parallel/ series components of the circuit. The first three parts are elementary, the answers are:

$$R_{(a)} = 0.6R$$

$$R_{(b)} = \frac{4}{7}R$$

$$R_{(c)} = 0.25R$$

Part (d) and (e) are much more difficult. They are both Wheatstone bridge circuits. In part (d), since the four branches are balanced (i. e. positions 1-4), there is no current through the centre resistor. An alternative method is to consider the voltage drop from A to B in the upper and lower branches - one will find that since the resistors have equal resistance the voltage in the mid-points in both branches are equal. Since the voltage difference between the two ends of the centre resistor is 0, the current through it is also 0. The equivalent resistance is:

$$R_{(d)} = R$$

We need to introduce the Kirchhoff's Laws before we can calculate the equivalent resistance of this circuit.

Law 2. *Kirchhoff's Voltage Law states that the sum of the potential changes around a loop in a circuit is equal to zero. It follows from the Faraday's Law of induction, which states that in a steady field,*

$$\oint \mathbf{E} \cdot d\mathbf{l} = 0 \tag{13}$$

Law 3. *Kirchhoff's Current (Junction) Law states that the currents converging and diverging from a junction must sum to zero regardless of the directionality taken. It follows from the conservation of charge.*

To solve this problem we first label the currents as follows:

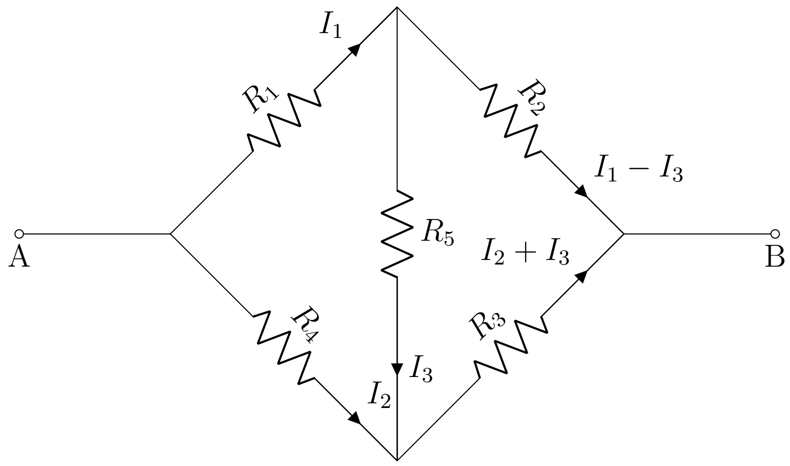

Figure 7: Labelling the currents in the Figure 1.5. The currents in the right-half loop is obtained using *Kirchhoff's Current Law.*

Consider the left-half loop and the right-half loop. Using *Kirchhoff's Voltage Law*, we may obtain the following two equations (Take clockwise as positive.)

$$2I_1R - I_2R + I_3R = 0 \tag{14}$$

$$\begin{aligned}(I_2 + I_3)R + I_3R - (I_1 - I_3)R = 0\\ -I_1R + I_2R + 3I_3R = 0\end{aligned} \tag{15}$$

Hence eliminating I_3 gives,

$$7I_1 = 4I_2 \tag{16}$$

and eliminating I_2 gives,

$$I_1 = 4I_3 \tag{17}$$

Suppose the voltage difference between A and B is V. Then,

$$R_{eq} = \frac{V}{I_1 + I_2} \tag{18}$$

Also, by considering the top branch we have

$$V = 3I_1R - I_3R \tag{19}$$

Hence using Equations 18 and 19 we have

$$R_{eq} = \frac{3I_1 - I_3}{I_1 + I_2}R \tag{20}$$

Finally using Equations 16, 17 and 20,

$$R_{eq} = \frac{3 - 0.25}{1 + 1.75}R = R$$

Surprising equal to part (d)!

Question 1.6

Describe how transformer work. How can you improve the performance of a transformer - and why? (3 Mar)

Solution:

An ideal transformer is formed by two coils wounding around a ferromagnetic core. Current I_1 is time-varying, and it generates a time-varying magnetic field in core. The changing magnetic flux induces a sinusoidal *emf* in the second wounding coil. This, by using *Faraday's Law of Induction*, generates a time-varying current in the second coil I_2. The different number densities of the coils will give different voltages.

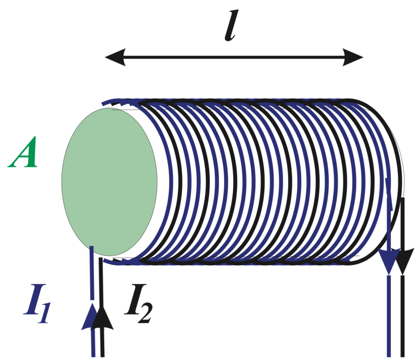

Figure 8: A model of a transformer. Taken from the lecture notes of IB Electromagnetism, University of Cambridge.

To answer how to improve the performance of a transformer, one has to first identiy that the main source of energy loss is via dissipation as heat. There are three methods suggested in the notes and textbooks and I am going to only list them here:

1. Use a copper wire with less electrical resistance (by using a thicker wire for example).
2. Include laminations to prevent the building up of large eddy currents.
3. Pick a ferromagnetic core of a larger relative permeability μ to "enhance" the field in the core.

Question 1.7

Design an experiment to measure the wavelength of a laser using diffraction experiments. You are given with a diffraction grating of a known slit separation, a double slit, a single slit (which you may use or not use), a screen, a measuring tape and a ruler with 0.5mm readings. Mention the related error and uncertainties you might come across. (4 Mar)

Solution:

This is an experimental physics question. It is important here to think about a few points:

1. What set-up should I build? What am I given with?
2. What is the relevant theory? What equations should I use? Have I done a similar experiment before?
3. Think hard about measurements at each step - what are the associated errors and uncertainties?
4. Is there a simpler set-up that I can use?

After considering these preliminary questions, try and draft up something in your head. Check by doing thought experiments that your set-up works. onlt then should you start writing.
Here are some suggestions of experiments you can use.

Two-slit experiment

1. Align laser beam on an optical rail. Shine light perpendicularly on the two-slits aperture.
2. Set up a screen distance D from the aperture.
3. Record the separation of fringes on the screen.
4. Measure the distance from the aperture to the screen using a measuring tape.
5. Using a relevant equation (see below), calculate the wavelength from the measured data.

You should recall the following equation:

$$\Delta x = \frac{\lambda D}{a} \tag{21}$$

where a is the slit separation and Δx is the fringe separation. You can measure the slit separation using a ruler (usually it is of order $\sim 10^{-6}m$ - you will only be able to measure it using a microscope).

Grating experiment: The procedure is the same as before. However, this time the fringes are not uniformly separated and obeys the equation:

$$d \sin\theta = n\lambda \tag{22}$$

d being the slit separation in grating (given). Angle θ can be found by using simple trigonometry:

$$\tan\theta = \frac{x}{D}$$

where x is the separation on the screen. Note that it is permissible to obtain a more accurate result by plotting a graph of $\sin\theta$ against the order n and drawing a best-fit line. The slope will be $\frac{\lambda}{d}$, and you can then calculate the wavelength.

Remark. *A laser pattern usually gives closely separated fringes. Using the small-angle approximation $\theta \approx \sin\theta \approx \tan\theta$, you can write Equation 22 as:*

$$x = \frac{n\lambda D}{d} \tag{23}$$

Hence you can plot the position of the fringes x (with respect to the centre point or zeroth order maximum; need not be accurate since does not affect slope) against the order n and do a χ^2 distribution to obtain the wavelength and its associated error.

Errors and Uncertainties:

1. The main contribution of your error comes from measurement of distances using the ruler and measuring tape.
2. We have used the approximation $D \gg x$. Is this true? (Fraunhofer vs Frensel Diffraction) It is always helpful to check if your set-up is in the right regime by doing a back-of-the-envelope calculation.
3. Is the small angle approximation good? (It is.)
4. Make sure you are using a coherent light source. (State it!) If I had used a lamp, then a single-slit must be added to create a coherent source.
5. How far should the distance be between the single and double-slit? It should ensure that the secondary waves created from the single slit is sufficiently far away such that they illuminate on the double slit in an orthogonal direction.

Question 1.8

A rollercoaster is performing a vertical circular loop. Suppose the track is smooth. Find the minimum initial speed (at the bottom) for the rollercoaster to perform a complete loop given that the radius of the vertical loop is R. (*Hint: The question is not as easy as it looks - think about the centripetal force when the rollercoaster is at its higher point!*) (5 Mar)

Solution:

We know that it is not as simple as energy conservation (from the hint). Centripetal force at the top is given by

$$F_{cent} = mg + N = m\frac{v^2}{R}$$

When the force is minimum the normal force is zero. Hence,

$$v_{top} = \sqrt{gR}$$

Now we use energy conservation to give

$$\frac{1}{2}mv^2 + mgh = const \tag{24}$$

$$\implies v_0 = \sqrt{5gR}$$

Question 1.9

Describe what happens to a metallic ball tied to the wall by a string between two oppositely charged plates. (6 Mar)

Solution:

This is just a simple conceptual question. I will list the things that will happen in point-form as follows:

1. Imagine ball starts at a plate - ball is charged as the same sign as the plate.
2. Electrical Repulsion drives ball away from plate.
3. Meanwhile, ball is attracted to the other plate.
4. When ball hits the plate it discharges and becomes charged with the opposite charge.
5. Same thing happens again... The system repeats and the ball is shuttled between the two plates.

Question 1.10

Why do you need angular momentum? Why is it quantised in the Bohr model? (7 Mar)

Solution:

This question is posted here simply for the sake of me trying to be funny. First the definition of angular momentum is as follows:

Definition 7. *Angular momentum* $\mathbf{L}$ *is defined as*

$$\mathbf{L} = \mathbf{r} \times \mathbf{p} \tag{25}$$

where $\mathbf{r}$ *is the radial vector and* $\mathbf{p}$ *is the momentum.*

Then the law of conservation of angular momentum can be stated.

Law 4. *Angular momentum s conserved if there is no external torque acting on the system.*

Although this is not in the core DSE syllabus, it forms the backbone of classical mechanics. It arises from the fact that we have rotational invariance - i. e. if you do the exact experiment in two systems, one of which is rotated about an axis of the other system, the results will be the same.

Bohr's Atom In the HKDSE, the fact that angular momentum is quantised is only stated as a fact (if I remember correctly - which means that all you can do is memorise it!). However, the reason why it is quantised is because of a complex structure of 3D quantum mechanics. You can understand it simply by the fact that we need standing waves to exist around the atom, hence L must be quantised. (Look up or ask me if you want more...)

Short Conceptual Questions - Thermodynamics

Question 2.1

What is temperature? How do you quantify it? Do you think it is an intuitive concept or a statistical concept?

Question 2.2

What is the heat capacity of a body? Suppose I am heating two identical objects with the same initial temperatures under the conditions of constant volume and constant pressure respectively. Do they have the same heat capacity? Why?

Question 2.3

What is latent heat? Where does it actually come from?

Question 2.4

Out of conduction, convection and radiation, which one do you think is the hardest process to quantify?

Short Conceptual Questions - Classical Mechanics

Question 3.1
What is the definition of a vector? How about a scalar? Why do we need two different quantities?

Question 3.2
How many degrees of freedom do you have in a kinematics problem?

Question 3.3
Does normal reaction and weight on a person standing on the floor constitute an action-reaction pair?

Question 3.4
Tension is constant in a string. Is this statement correct?

Question 3.5
Why do we resolve forces into orthogonal/ perpendicular directions?

Question 3.6
How can you convert a $v - t$ graph to an $s - t$ or $a - t$ graph?

Question 3.7
What is energy? What is momentum? What is the basis on that they are conserved?

Question 3.8
Can we have a collision that does not conserve momentum? How?

Question 3.9
What is the energy? What is work? How are they related?

Question 3.10
What is the centripetal force? How do you draw that on a force diagram?

Question 3.11
What is omega in circular motion?

Question 3.12
What is the definition of a radian? Why do you use radian formulae in physics?

Question 3.13
What is g? How is this a field (is this in the syllabus)?

Question 3.14
Find the expression for the velocity of an object travelling in a gravitational orbit. How is r, the radius of the orbit, and the period T related?

Short Conceptual Questions - Waves and Optics

Question 4.1

What is the thin lens equation? Is there a limitation for which we can use it? What is it?

Question 4.2

Small-angle approximation is prevalent in some optical equations. How good is it?

Short Conceptual Questions - Electromagnetism

Question 5.1
What happens to the electric field/ potential when we are on the point charge?

Question 5.2
We have discussed the differences between field and potential. Why do you think that using potentials to analyse problems are easier?

Question 5.3
Often energy dissipation is discussed in the context of an electrical circuit. What is the energy in an electrostatic field?

Question 5.4
How do I convert an AC to a DC?

Question 5.5
What are magnetic fields? Why are they so weird?

Question 5.6
Why aren't there any magnetic monopoles?

Question 5.7
Why do we have the Lenz Law anyways?

Question 5.8
Why are electric fields and magnetic fields related anyways? (They have no relationships a priori.)

Question 5.9
Why do we need AC anyways? Why use a more complicated form?

Short Conceptual Questions - Atomic Physics

Question 6.1

Is $E = mc^2$ always true (in the relativistic context)?