

How to Construct Written Practical Items in Physics Examinations

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This article analyzes the technical and conceptual errors in three items in the written practical papers of the A-level examination papers, as well as mistakes in the corresponding solutions from the official marking scheme. Their causes and possible influences are discussed. Improvement for specific items and general preventive measures are proposed.

Public examination papers are supposed to be reliable and valid test instruments for assessing pupils' achievement (e.g., Aiken, 1988). In Hong Kong, results of the A-level examinations are important indicators of pupils' academic achievement, and are used in selection for employment or tertiary places. As a test instrument of high-stake examinations, the A-level papers of each subject are usually constructed by a moderation committee consisting of university professors and experienced teachers. Items are carefully selected and scrutinized by the moderation committee in lengthy meetings over a period of several months to ensure high validity and discrimination, and to minimize technical and conceptual errors. Statistical indexes such as biserial coefficients and facility values (e.g., Guilford & Fruchter, 1978/1981, pp. 304–308) are computed from candidates' scores after the test to further assure consistency among items and across papers in the same subject.

Like other science subjects, physics is a discipline that places great emphasis on both theoretical conceptual understanding and experimental processing skills. Assessment of pupils' ability to design and conduct investigations are usually made through performance in the practical examination as well as the written papers. In the written papers, items can be set to test pupils' ability to select suitable parameters, analyze data, and

identify source of errors in a practical setting. These items also serve to discourage pupils from memorizing experiments by rote and focusing on “cook-book” experiments only, but to encourage them to engage in investigations that aim at applying scientific knowledge to solve problems in realistic and novel situations.

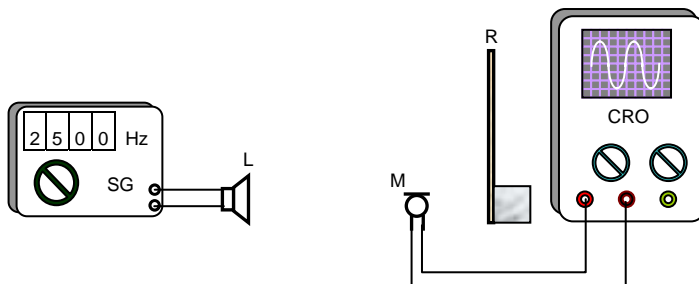
Despite the formal and painstaking quality assurance procedures, errors do occur occasionally in the practical items of the written papers of the A-level Physics examination. In this article, we report three examples of such errors that occurred in the past few years. The purpose of reporting and analyzing these errors is not to find fault with the examination, but to expose some reckless mistakes that may have been overlooked by the subject experts of the moderation committee. Such mistakes may be propagated through the examination papers to science teachers, and consequently have adverse effects on pupils’ conceptual development. This article aims at alerting science teachers to these instructional pitfalls. Through the identification of these pitfalls and deliberation on their causes, teachers can help their students develop and consolidate their understanding in the concerned areas.

In the following discussion, only the faulty items with their related parts in the question papers, and the corresponding solutions in the “Marking Scheme” (hereafter referred to as “MS”) are presented, with slight modifications in wording to avoid copyright infringement. The items quoted in this article are all related to electrical measurement involving the use of a cathode ray oscilloscope (CRO). Although the experiments concerned can be carried out readily in a school science laboratory, it seems that the item setter had just constructed the items theoretically without actually working out the practical details. Besides pointing out the mistakes and exploring the causes, an attempt is made to rewrite each item to convey a more proper scientific view. This will help teachers and pupils develop a better understanding of the concepts and skills involved. When doing this, we try to preserve the original context and objectives instead of replacing by more sophisticated alternatives the original method.

Analysis of Item 1

The Question

The setup shown in Figure 1 is used to determine the speed of sound in air.

Figure 1 Stationary Sound Wave in Free Space

With the stationary waves set, the microphone M detects alternative maximum and minimum signals when moving between the loudspeaker L and the plane reflector R. Results for different signal frequencies are recorded by a student in Table 1.

Table 1 Node-to-node Separation at Different Frequencies

Frequency of SG f / kHz	Position of the 1st node and the 7th node l / cm	Wavelength λ / cm	Period T / ms
2.500	27.0, 68.7		
2.941	16.0, 51.5		
3.571	18.7, 48.1		
4.545	31.8, 55.5		
6.250	26.4, 44.7		

- (a) i. Complete Table 1 (Hint: $\lambda = 2 \times$ Average node-to-node separation).
 ii. Plot a graph of wavelength λ against period T .
 iii. Hence find the speed of sound in air.
 (b) Explain why the graph does not pass through the origin.
 (c) Explain the advantage of performing the experiment outdoors.

Answers Provided in the MS

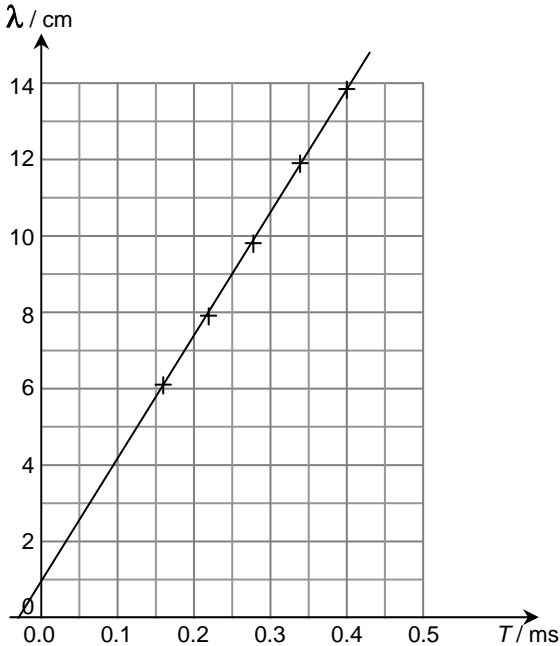
- (a) i. See Table 2

Table 2 Relation Between λ and T

Wavelength λ / cm	Period T / ms
13.9	0.40
11.8	0.34
9.8	0.28
7.9	0.22
6.1	0.16

ii. See Figure 2

Figure 2 Relation Between Wavelength and Period



iii. From the slope of the graph, $v = \text{slope} = 324 \text{ m s}^{-1}$

- (b) There exists systematic error in the measurement of wavelength (positions of M) or/and frequencies.
 (c) There is less reflection from walls or nearby objects.

Errors in Item 1

1. The table has only face value. In practice, the performer should first locate the most sensitive frequency that the microphone can respond and carry out the experiment at the best frequency instead of making measurement at oddly designated frequencies.
2. In position measurement of part (b), the same systematic error of +1.0 cm in each data point is beyond our wisdom to understand. Similarly, in time measurement, since the period of the sound wave can be counterchecked by the CRO, it seems that the same systematic error of

–0.03 ms in each point (about –7.5% in the first measurement, but up to –19% in the last) is also consistently inconsistent. However, a random error of ± 0.02 ms, a sensible one if a CRO is used for time measurement, would generate a straight line with an x-intercept very close to the origin. Ironically, the correct answer is not mentioned in the MS.

3. The question in part (c) is not realistic and the corresponding answer is incorrect. Anyone who has performed the experiment in a laboratory would have noticed that the reflection of sound wave from walls meters away has little contribution to the error. On the other hand, there is no advantage in doing the experiment outdoors because reflection of sound from the surface of the bench cannot be avoided. The reflection from the only nearby object, the CRO, can be prevented by placing it behind the reflecting plate.

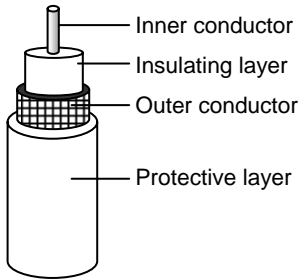
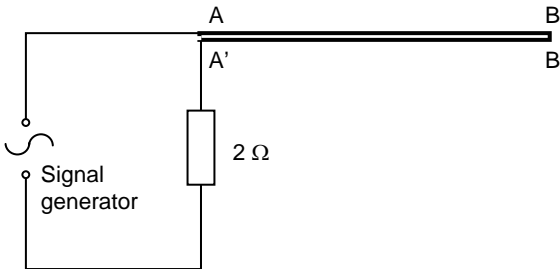
Ways to Improve Item 1

1. Compare the pupils' experimental results with that obtained by the teacher using a single frequency. Ask the pupils to deliberate why “using different frequencies blindly” is not necessarily better than “using the frequency at which the microphone is most sensitive.”
2. Redesign Table 1 in the question such that the line constructed by the pupils misses the origin by no more than 0.2 cm. In the MS, random errors in time and/or distance measurement should be accepted as a correct answer. On the contrary, the existence of systematic error is just a description of the result. Answers in such terms should not be awarded with any marks unless the cause and direction are explained.
3. Part (c) can be reconstructed to assess more worthwhile skills, such as “What precautions should be taken in order to avoid unwanted reflections from nearby objects, including the CRO?”

Analysis of Item 2

The Question

Figure 3a shows the free end of a 3 m coaxial cable consisting of an inner conductor, an insulating layer, an outer conductor and a protective layer.

Figure 3a Configuration of a Coaxial Cable**Figure 3b Circuit to Measure the Inductance of a Coaxial Cable**

The inner core and the outer mesh can be represented as conductors AB and A'B' respectively. The cable can be treated as a single looped inductor by connecting one of the ends, say B and B', together in a circuit (Figure 3b). To measure its inductance L , the free ends A and A' are connected to a signal generator and a $2\ \Omega$ resistor (Figure 3b). It is known that the inductance per unit length of the cable, L_0 , is of the order $10^{-7}\ \text{H m}^{-1}$ (Feynman, 1964, p. 24–3). There are two frequencies, 100 kHz and 1 MHz, that can be chosen for the measurement. Which one is a better choice? Explain briefly.

Answers Provided in the MS

From $X_L = \omega L$

$$\text{At } 100\ \text{kHz}, X_L = \omega L = 2\pi \times 100 \times 10^3 \times 10^{-7} = 0.06\ \Omega\ \text{m}^{-1}$$

$$\text{At } 1\ \text{MHz}, X_L = \omega L = 2\pi \times 10^6 \times 10^{-7} = 0.6\ \Omega\ \text{m}^{-1}$$

1 MHz is better since the order of magnitude of X_L is comparable to that of the resistor.

Errors in Item 2

Although the calculation in the MS is correct, the reason for choosing 1 MHz is problematic. The answer depends on what instrument is used and how measurement is done. In practice, the reactance ($3 \text{ m} \times 0.06 \Omega \text{ m}^{-1}$) of the inductor at 100 kHz is difficult to measure because its magnitude is close to the stray inductance (Harnwell, 1949, p. 330) and the contact resistance in an actual circuit. However, nothing is mentioned about stray inductance and contact resistance in the MS.

In theory, if R is known in an LR circuit and a CRO is used for measurement, L can be obtained in a number of ways (Mak, 2002). Just to mention a few:

- Obtaining L by comparing the voltages, say V_L and V_Z , or V_R and V_Z .
- Finding the slope of the R-trace and calculate L from $L = V_L / (dI/dt)$.
- Finding the difference in zero-crossings ΔT between the R-trace

and the Z-trace, then calculate L using the relation $\tan(\omega\Delta T) = \frac{\omega L}{R}$.

Even if we limit our choices to the comparison of voltages, one can show easily that there is no preference between 100 kHz and 1 MHz if the ratio V_L/V_Z is used to find L .

Referring back to the circuit in Figure 3b, with all voltage readings given in peak-to-peak values, L can be obtained by solving the equation:

$$V_L = I\omega L = \frac{V_Z\omega L}{Z} = \frac{V_Z\omega L}{\sqrt{(\omega L)^2 + R^2}} \quad (2.1)$$

Using the results supplied in the MS, the reactance X_L for the 3 m cable at 100 kHz and 1 MHz is 0.18Ω and 1.8Ω respectively.

From equation (2.1):

$$\text{At 100 kHz, } V_L \approx 0.0896 V_Z$$

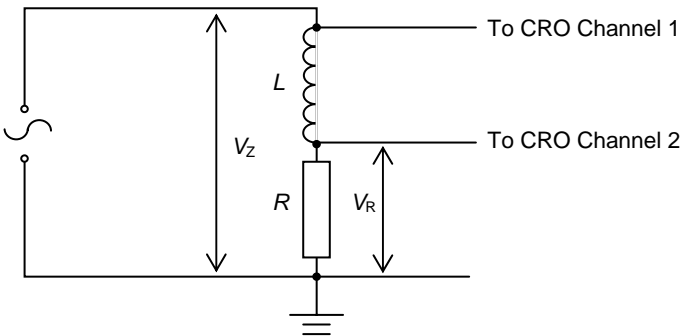
$$\text{At 1 MHz, } V_L \approx 0.6690 V_Z$$

For simplicity, we assume that $V_Z \geq 1.0 \text{ V}$ (the voltage supplied by the signal generator). Since the sensitivity of a school model CRO is no less than 10 mV/cm , by using different V-gain settings, V_L can be measured with a percentage error fairly independent to the choice of frequency.

Ways to Improve Item 2

1. To avoid errors created by contact resistance and stray inductance, a larger resistance and a longer cable should be used. A concrete choice, among others, is to replace the $2\ \Omega$ resistor by one with $20\ \Omega$ and a 3 m cable by a 30 m cable.
2. Using the same notations and phrasings as in the original item, a definite answer can be obtained by fixing the choice of voltages measured. This can be done by adding a sentence “A CRO is used to measure V_R and V_Z (Figure 4)” after introducing the order of magnitude of the inductance. Figure 4 is just the circuit diagram of Figure 3b in standard symbols.

Figure 4 RL Circuit in Standard Circuit Symbols



$$\text{From } V_R = IR = \frac{V_Z R}{\sqrt{(\omega L)^2 + R^2}}$$

$$\text{Solving for } L, \text{ we have } \omega L = R \left[\left(\frac{V_Z}{V_R} \right) - 1 \right]^{\frac{1}{2}}$$

When $f = 100\ \text{kHz}$, $\frac{V_Z}{V_R}$ is very close to 1 (≈ 1.004). This results in a

large percentage error in L measurement. However, if 1 MHz is used,

$\frac{V_Z}{V_R}$ is about 1.35, the result of measurement being much more

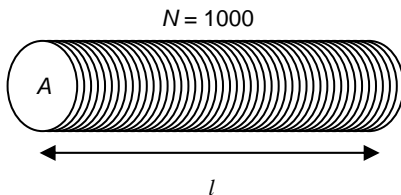
acceptable.

Analysis of Item 3

The Question

A solenoid with number of turns $N = 1000$ turns has a cross-sectional area $A = 1.96 \times 10^{-3} \text{ m}^2$ and length $l = 0.5 \text{ m}$ (Figure 5).

Figure 5 Geometry of a Solenoid



- (a) Assume no flux leakage, find the inductance of the solenoid using

formula $L = \mu_0 \frac{N^2 A}{l}$ where $\mu_0 =$ permeability of free space $= 4\pi \times 10^{-7} \text{ H m}^{-1}$

- (b) The solenoid is connected to a 3 V battery and an external resistor R_0 (Figure 6). When the switch S is opened, the initial fall of the current i in the discharging RL loop is shown in Figure 7. Find the experimental values of R and L , where r is the resistance of the windings of the solenoid and $R = R_0 + r$ is the total resistance of the RL loop.
- (c) Account for the difference between the calculated value and the experimental value.

Figure 6 The Charging and Discharging RL Circuit

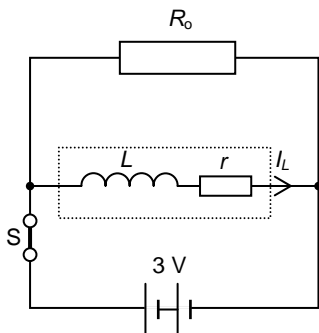
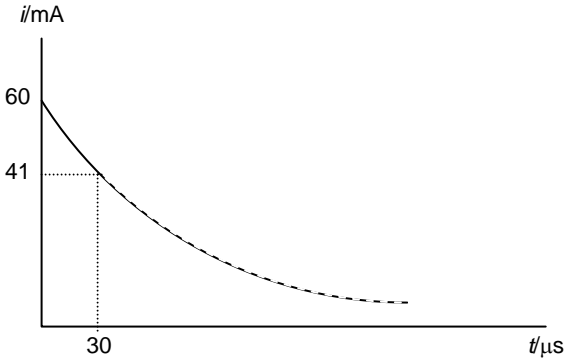


Figure 7 The Initial Fall of Current in the RL Loop**Answers Provided in the MS**

- (a) Assume the same flux linkage for all turns, the calculated value of the inductance is

$$L = \mu_0 \frac{N^2 A}{l} = 4\pi \times 10^{-7} \times \frac{10^6 \times 1.96 \times 10^{-3}}{0.5} \text{ H} = 4.93 \text{ mH}$$

- (b) Assume that at $t = 0$, the induced emf is 3V.

$$R = \frac{V}{I} = \frac{3 \text{ V}}{60 \text{ mA}} = 50 \ \Omega$$

From $I = I_0 e^{-\frac{Rt}{L}}$, for small t ,

$$I \approx I_0 \left(1 - \frac{Rt}{L}\right)$$

Slope of linear portion is

$$m = -\frac{\Delta i}{\Delta t} = -\frac{(60 - 41) \text{ mA}}{30 \mu\text{s}} = -0.63 \times 10^3 \text{ A s}^{-1}$$

$$\therefore L = -\frac{RI_0}{m} = \frac{50 \ \Omega \times 60 \text{ mA}}{0.63 \times 10^3 \text{ A s}^{-1}} = 4.73 \text{ mH}$$

- (c) Stray inductance / flux leakage, etc.

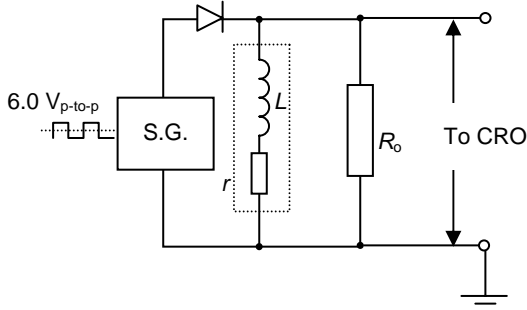
Errors in Item 3

1. In the A-level Physics curriculum, there is no simple device for measuring directly the time variation of current through the solenoid down to the μs level.
2. The assumption that the initial induced emf is 3 V in the MS is not only incorrect (Jackson, 1965, p. 231), but also a serious misconception.
3. Neither L nor R can be found from the information given in the decay curve.
4. The magnitude of stray inductance is of the order of only $1 \mu\text{H}$ and should not be taken as an acceptable answer to account for the difference of 0.2 mH between the calculated value and the experimental value.

Ways to Improve Item 3

- 1 One simple way to obtain a decay curve in an RL loop is to replace the 3 V battery by a signal generator and the switch S by a diode (Figure 8a). The time variation of voltage V across R_o can be observed on a CRO screen. With suitable V-gain and time base settings, a decay curve is displayed when the diode is in reverse bias.

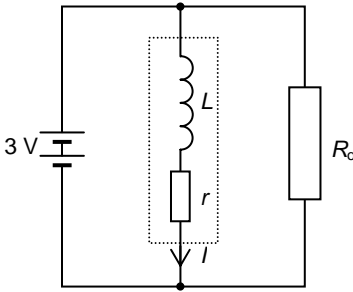
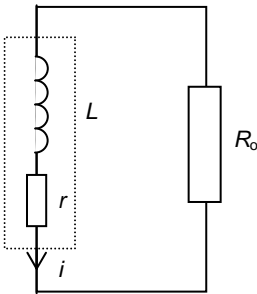
Figure 8a Circuit to Show the Decay Curve in an LR Loop



2. In order to obtain a value for L and R in part (b), R_o must be given. To make the least change, we can set $R_o = 1.0 \Omega$. In this way, the voltage across R_o is numerically equal to the current through it. Here is our solution for part (b):

In the charging half-cycle (Figure 8b), assume that there is no voltage loss in the diode, the steady state current through the solenoid is:

$$I_o = \frac{3V}{r} \quad (3.1)$$

Figure 8b Equivalent Circuit of the Charging Half-cycle**Figure 8c** Equivalent Circuit of the Discharging Half-cycle

In the discharging half-cycle (Figure 8c), the solenoid will act as a momentarily source of emf as its magnetic field collapses. Since the current through the solenoid cannot change instantly, the initial current in the discharge loop is just the steady state current through L in the charging loop.

From equation (3.1) and Figure 7, the resistance of the solenoid is

$$r = \frac{3.0 \text{ V}}{0.06 \text{ A}} = 50.0 \ \Omega$$

and the resistance of the RL loop is

$$R = r + R_0 = 51.0 \ \Omega$$

Once R is known, we can proceed in the exactly same way as the solution in the MS.

$$\therefore L = -\frac{RI_o}{m} = \frac{51 \ \Omega \times 60 \text{ mA}}{0.63 \times 10^3 \text{ A s}^{-1}} = 4.86 \text{ mH}$$

3. Instead of stray inductance, the uncertainty in slope measurement should be considered as an acceptable answer to account for the difference in parts (a) and (b).

Consequences of Using Unrealistic Items and Providing Misleading Answers in the MS

Mistakes in the test paper and incorrect answers in the MS should be avoided because they are unfair to candidates. In particular, they penalize good students because a correct answer may be given no mark, and the time wasted in tackling the problem is given no compensation. Worst of all, items with no solution panic some students and affect their performance in the whole paper.

Although the MS is intended to be used by teachers only, in reality, items or item-types from past papers and their solutions from the MS are used extensively by teachers to prepare pupils for public examinations. Misconceptions in the MS propagating from teacher to student directly via past-paper drills, or indirectly via end-of-chapter assignment in textbooks year after year, produce a profound and long-term negative influence to the teaching and learning of physics. To be specific, the possible influence of each case is analyzed in the following paragraphs.

Of all the three items, item 1 may be least detrimental because it does not lead to any misconception. Since the table in the item stem is not authentic and the procedure is superfluous and improper, it might encourage students the bad habit of making up forged results in an experimental report. Also, part (c) of item 1 encourages pupils to answer by blind guesses or trial and error rather than through critical thinking.

The solution from the MS in item 2 might lead to the following two misconceptions:

In measurement of impedance using the method of voltage comparison, the impedance involved must have the same order of magnitude.

The percentage error in voltage measurement increases as the magnitude of the voltage decreases.

The first statement is true for impedance measurement using a Wheatstone bridge but not true for an LR or CR circuit. The second statement is true for a moving coil voltmeter with a single range, but not true for a CRO with multiple V-gain settings.

In item 3, the assumption that the initial induced emf is 3 V in the MS might lead to the following misconception:

The initial induced emf generated in an inductor when the circuit is interrupted is equal to the emf of the battery in the original circuit before interruption.

The correct statement should be:

The initial induced emf generated in an inductor when the circuit is interrupted is equal to the product of “current through the inductor” just before interruption and the total “resistance in the new circuit loop.”

In error treatment, stray inductance has a large contribution in item 2, but not in item 3. However, the answers in the MS seem to tell us the opposite. These confusing conceptions in official documents from the Examination Board(s) might encourage pupils to use rote memory and trial-and-error strategy for problem solving.

Can Mistakes in Practical Items Be Avoided?

In order to cater for the varied abilities of students, A-level textbook authors often present physics ideas in a simplified form instead of referring to the formal concepts which may be too sophisticated for the comprehension of A-level students. A-level examiners face the same challenge when setting assessment items for students. To simplify a complex idea accurately without connoting ambiguity or misconception requires deep conceptual understanding as well as skills in construction of assessment items. The errors committed by examiners as presented in this article are worthy of notice, and the suggestions for improvement may hopefully contribute to the relatively scarce literature in this area (Stock, 1986).

It is believed that mishaps quoted here are not isolated events. We hope that Examination Boards all over the world could be alerted by the points raised up in this article. We also welcome teacher trainers in other institutes to use items discussed here as exercises of item analysis for their student teachers.

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