The internal assessment criteria

The new assessment model uses five criteria to assess the final report of the individual investigation with the following raw marks and weightings assigned:

Personal engagement	Exploration	Analysis	Evaluation	Communication	Total
2 (8%)	6 (25%)	6 (25%)	6 (25%)	4 (17%)	24 (100%)

Levels of performance are described using multiple indicators per level. In many cases the indicators occur together in a specific level, but not always. Also, not all indicators are always present. This means that a candidate can demonstrate performances that fit into different levels. To accommodate this, the IB assessment models use markbands and advise examiners and teachers to use a **best-fit approach** in deciding the appropriate mark for a particular criterion.

Teachers should read the guidance on using markbands in the group 4 subject guides, in the section "Using assessment criteria for internal assessment" before starting to mark. It is also essential to be fully acquainted with the marking of the exemplars in the teacher support material. The precise meaning of the command terms used in the criteria can be found in the glossary of the subject guides.

Personal engagement

This criterion assesses the extent to which the student engages with the exploration and makes it their own. Personal engagement may be recognized in different attributes and skills. These could include addressing personal interests or showing evidence of independent thinking, creativity or initiative in the designing, implementation or presentation of the investigation.

Mark	Descriptor
0	The student's report does not reach a standard described by the descriptors below.
1	**The evidence of personal engagement with the exploration is limited with little independent thinking, initiative or creativity.** The justification given for choosing the research question and/or the topic under investigation does not demonstrate **personal significance, interest or curiosity**. There is little evidence of **personal input and initiative** in the designing, implementation or presentation of the investigation.
2	**The evidence of personal engagement with the exploration is clear with significant independent thinking, initiative or creativity.** The justification given for choosing the research question and/or the topic under investigation demonstrates **personal significance, interest or curiosity**. There is evidence of **personal input and initiative** in the designing, implementation or presentation of the investigation.

Exploration

This criterion assesses the extent to which the student establishes the scientific context for the work, states a clear and focused research question and uses concepts and techniques appropriate to the Diploma Programme level. Where appropriate, this criterion also assesses awareness of safety, environmental and ethical considerations.

Mark	Descriptor
0	The student's report does not reach a standard described by the descriptors below.
1–2	The topic of the investigation is identified and a research question of some relevance is **stated but it is not focused.** The background information provided for the investigation is **superficial** or of limited relevance and does not aid the understanding of the context of the investigation. The methodology of the investigation is only appropriate to address the research question to a very limited extent since it takes into consideration few of the significant factors that may influence the relevance, reliability and sufficiency of the collected data. The report shows evidence of limited awareness of the significant safety, ethical or

environmental issues that are **relevant to the methodology of the investigation***.

The topic of the investigation is identified and a relevant but not fully focused research question is described.

The background information provided for the investigation is mainly appropriate and relevant and aids the understanding of the context of the investigation.

3–4 The methodology of the investigation is mainly appropriate to address the research question but has limitations since it takes into consideration only some of the significant factors that may influence the relevance, reliability and sufficiency of the collected data.

The report shows evidence of some awareness of the significant safety, ethical or environmental issues that are **relevant to the methodology of the investigation***.

The topic of the investigation is identified and a relevant and fully focused research question is clearly described.

The background information provided for the investigation is entirely appropriate and relevant and enhances the understanding of the context of the investigation.

5–6 The methodology of the investigation is highly appropriate to address the research question because it takes into consideration all, or nearly all, of the significant factors that may influence the relevance, reliability and sufficiency of the collected data.

The report shows evidence of full awareness of the significant safety, ethical or environmental issues that are **relevant to the methodology of the investigation***.

* This indicator should only be applied when appropriate to the investigation. See exemplars in TSM.

Analysis

This criterion assesses the extent to which the student's report provides evidence that the student has selected, recorded, processed and **interpreted** the data in ways that are relevant to the research question and can support a conclusion.

Mark	Descriptor
0	The student's report does not reach a standard described by the descriptors below.
1–2	The report includes **insufficient relevant** raw data to support a valid conclusion to the research question. Some **basic** data processing is carried out but is either too **inaccurate or too insufficient to lead to a valid** conclusion.

	The report shows evidence of little consideration of the impact of measurement uncertainty on the analysis. The processed data is incorrectly or insufficiently interpreted so that the conclusion is invalid or very incomplete.
3–4	The report includes relevant but incomplete quantitative and qualitative raw data that could support a simple or partially valid conclusion to the research question. Appropriate and sufficient data processing is carried out that could lead to a broadly valid conclusion but there are significant inaccuracies and inconsistencies in the processing. The report shows evidence of some consideration of the impact of measurement uncertainty on the analysis. The processed data is interpreted so that a broadly valid but incomplete or limited conclusion to the research question can be deduced.
5–6	The report includes sufficient relevant quantitative and qualitative raw data that could support a detailed and valid conclusion to the research question. Appropriate and sufficient data processing is carried out with **the accuracy** required to enable a conclusion to the research question to be drawn that is fully **consistent** with the experimental data. The report shows evidence of full and appropriate consideration of the impact of measurement uncertainty on the analysis. The processed data is correctly interpreted so that a completely valid and detailed conclusion to the research question can be deduced.

Evaluation

This criterion assesses the extent to which the student's report provides evidence of evaluation of the investigation and the results with regard to the research question and the accepted scientific context.

Mark	Descriptor
0	The student's report does not reach a standard described by the descriptors below.
1–2	A conclusion is **outlined** which is not relevant to the research question or is not supported by the data presented. The conclusion makes superficial comparison to the accepted scientific context.

Strengths and weaknesses of the investigation, such as limitations of the data and sources of error, are **outlined** but are restricted to an **account** of **the practical** or **procedural issues** faced.

The student has **outlined** very few realistic and relevant suggestions for the improvement and extension of the investigation.

A conclusion is **described** which is relevant to the research question and supported by the data presented.

A conclusion is described which makes some relevant comparison to the accepted scientific context.

3–4 Strengths and weaknesses of the investigation, such as limitations of the data and sources of error, are **described** and provide evidence of some awareness of the **methodological issues*** involved in establishing the conclusion.

The student has **described** some realistic and relevant suggestions for the improvement and extension of the investigation.

A detailed conclusion is **described and justified** which is entirely relevant to the research question and fully supported by the data presented.

A conclusion is correctly **described and justified** through relevant comparison to the accepted scientific context.

5–6 Strengths and weaknesses of the investigation, such as limitations of the data and sources of error, are **discussed** and provide evidence of a clear understanding of the **methodological issues*** involved in establishing the conclusion.

The student has **discussed** realistic and relevant suggestions for the improvement and extension of the investigation.

*See exemplars in TSM for clarification.

Communication

This criterion assesses whether the investigation is presented and reported in a way that supports effective communication of the focus, process and outcomes.

Mark	Descriptor
0	The student's report does not reach a standard described by the descriptors below.

1–2	**The presentation of the investigation is unclear, making it difficult to understand the focus, process and outcomes.** The report is not well structured and is unclear: the necessary information on focus, process and outcomes is missing or is presented in an incoherent or disorganized way. The understanding of the focus, process and outcomes of the investigation is obscured by the presence of inappropriate or irrelevant information. There are many errors in the use of subject-specific terminology and conventions*.
3–4	**The presentation of the investigation is clear. Any errors do not hamper understanding of the focus, process and outcomes.** The report is well structured and clear: the necessary information on focus, process and outcomes is present and presented in a coherent way. The report is relevant and concise thereby facilitating a ready understanding of the focus, process and outcomes of the investigation. The use of subject-specific terminology and conventions is appropriate and correct. Any errors do not hamper understanding.

*For example, incorrect/missing labelling of graphs, tables, images; use of units, decimal places. For issues of referencing and citations refer to the "Academic honesty" section in the guide.

Guidance for the use of the internal assessment criteria

The internally assessed component of the course is divided into five sections.

- Personal engagement
- Exploration
- Analysis
- Evaluation
- Communication

Each section aims to assess a different aspect of the student's research abilities. The sections are differently weighted to emphasize the relative contribution of each aspect to the overall quality of the investigation. As the investigations, and therefore the approaches to the investigation, will be specific to each student, the marking criteria are not designed to be a tick-chart markscheme and each section is meant to be seen within the context of the whole. As such, a certain degree of interpretation is inevitable. The following tips are designed to help focus on the intention of each section, rather than be seen as a definitive approach.

Personal engagement

The emphasis within this section is on individuality and creativity within the investigation. The question to ask is, has the chosen research question been devised as a result of the personal experience of the student? The question could be a result of observations made in the student's own environment or ideas that the student has had as the result of learning, reading or experimenting in class. The investigation does not have to be ground-breaking research, but there should be an indication that independent thought has been put into the choice of topic, the method of inquiry and the presentation of the findings. The topic chosen should also be of suitable complexity. If the research question is very basic or the answer self-evident then there is little opportunity to gain full marks for exploration and analysis as the student will not have the opportunity to demonstrate his or her skills.

Exploration

The issue here is the overall methodology. Students need to take their individual ideas and translate them into a workable method. Students must also demonstrate the thinking behind their ideas using their subject knowledge. The information given must be targeted at the problem rather than being a general account of the topic matter, in order to demonstrate focus on the issues at hand.

What needs to be seen is a precise line of investigation that can be assessed using scientific protocols. It is then expected that the student gives the necessary details of the method in terms of variables, controls and the nature of the data that is to be generated. This data must be of sufficient quantity and treatable in an appropriate manner, so that it can generate a conclusion, in order to fulfill the criteria of analysis and evaluation. If the method devised does not lead to sufficient and appropriate data, this will lead to the student being penalized in subsequent sections where this becomes the crux of the assessment.

Health and safety is a key consideration in experimental work and forms part of a good method. If the student is working with animals or tissue, it is reasonable to expect there to be evidence that the guidelines for the use of animals in IB World Schools have been read and adhered to. The use of human subjects in experiments is also covered by this policy. If the student is working with chemicals, some explanation of safe handling and disposal would be expected. Full awareness is when all potential hazards have been identified, with a brief outline given as to how they will be addressed. It is only acceptable for there to be no evidence of a risk assessment if the investigation is evidently risk-free—such as in investigations where a database or simulation has been used to generate the data.

Analysis

At the root of this section is the data generated and how it is processed. If there is insufficient data then any treatment will be superficial. It is hoped that a student would recognize such a lack and revisit the method before the analysis is arrived at. Alternatively, the use of databases or simulations to provide sufficient material for analysis could help in such situations.

Any treatment of the data must be appropriate to the focus of the investigation in an attempt to answer the research question. The conclusions drawn must be based on the evidence obtained from the data rather than on assumptions. Given the scope of the internal assessment and the time allocated, it is more than likely that variability in the data will lead to a tentative conclusion. This should be recognized and the extent of the variability considered. The variability should be demonstrated and explained and its impact on the conclusion fully acknowledged. It is important to note that, in this criterion, the word "conclusion" refers to a deduction based on direct interpretation of the data, which is based on asking questions such as: What does the graph show? Does any statistical test used support the conclusion?

Evaluation

Although it may appear that the student is asked to repeat the analysis of the data and the drawing of a conclusion again in the evaluation, the focus is different. Once again the data and conclusion come under scrutiny but, in the evaluation, the conclusion is placed into the context of the research question. So, in the analysis, it may be concluded that there is a positive correlation between x and y; in the evaluation, the student is expected to put this conclusion into the context of the original aim. In other words, does the conclusion support the student's original thinking in the topic? If not, a consideration of why it does not will lead into an evaluation of the limitations of the method and suggestions as to how the method and approach could be adjusted to generate data that could help draw a firmer conclusion. Variability of the data may well be mentioned again in the evaluation as this provides evidence for the reliability of the conclusion. This will also lead into an assessment of the limitations of the method. It is the focus on the limitations that is at issue in the evaluation, rather than a reiteration that there is variability.

Communication

The marking points for communication take the entire write-up into consideration. If a report is clearly written and logically presented there should be no need for the teacher to re-read it. The information and explanations should be targeted at the question in hand rather than being a general exposition of the subject area; in other words, the report should be focused. The vocabulary should be subject-specific and of a quality appropriate to Diploma Programme level. The subject-specific conventions that can be expected are the correct formats for graph and tables and cell headings, correct use of units and the recording of errors. This is not to say that the presentation needs to be faultless to gain full marks. Minor errors are acceptable as long as they do not have a significant bearing on understanding or the interpretation of the results.

Errors and uncertainties in physics

The consideration and appreciation of the significance of the concepts of errors and uncertainties helps to develop skills of inquiry and thinking that are not only relevant to the group 4 sciences. The evaluation of the reliability of the data upon which conclusions can be drawn is at the heart of a wider scientific method, which is explained in section 3 of the "Nature of science" part of the subject guide. Errors and uncertainties are addressed in "Topic 1.2: Uncertainties and error" of the subject guide and this topic can be very effectively treated through the practical scheme of work.

The treatment of errors and uncertainties is also directly relevant in the internal assessment criteria of:

- **Exploration** ("The methodology of the investigation is highly appropriate to address the research question because it takes into consideration all, or nearly all, of the significant factors that may influence the relevance, reliability and sufficiency of the collected data.")
- **Analysis** ("The report shows evidence of full and appropriate consideration of the impact of measurement uncertainty on the analysis.")
- **Evaluation** ("Strengths and weaknesses of the investigation, such as limitations of the data and sources of error, are discussed and provide evidence of a clear understanding of the methodological issues involved in establishing the conclusion.")

Exploration

See exemplars that are relevant to addressing errors and uncertainties in the "Assessed student work" section of the TSM.

Analysis

The analysis criterion assesses the extent to which the student's report provides evidence that he or she has selected, recorded, processed and interpreted the data in ways that are relevant to the research question and can support a conclusion.

- The report includes sufficient relevant **quantitative and qualitative raw data** that could support a detailed and valid conclusion to the research question.
- Appropriate and sufficient **data processing** is carried out with the accuracy required to enable a

conclusion to the research question to be drawn that is fully consistent with the experimental data.
- The report shows evidence of full and appropriate **consideration of the impact of measurement uncertainty on the analysis.**
- The processed data is correctly interpreted so that a completely valid and detailed conclusion to the research question can be deduced.

Quantitative and qualitative raw data

All physics students are expected to deal with uncertainties throughout their investigations.

When numerical data is collected, values cannot be determined exactly, regardless of the nature of the scale or the instrument. If the mass of an object is determined with a digital balance reading to 0.1 g, the actual value lies in a range above and below the reading. This range is the uncertainty of the measurement. If the same object is measured on a balance reading to 0.001 g, the uncertainty is reduced, but it can never be completely eliminated. When recording raw data, estimated uncertainties should be indicated for all measurements.

There are different conventions for recording uncertainties in raw data.

- The simplest convention is the least count, which simply reflects the smallest division of the scale, for example ±0.01 g on a top pan balance.
- The instrument limit of error is usually no greater than the least count and is often a fraction of the least count value. For example, an analogue ammeter is often read to half of the least count division, which would mean that a value of 23 mA becomes 23.0 mA (±0.5 mA). Note that the value is now cited to one extra decimal place so as to be consistent with the uncertainty.
- The estimated uncertainty takes into account the concepts of least count and instrument limit of error but also, where relevant, higher levels of uncertainty as indicated by an instrument manufacturer.

Qualitative and quantitative comments about errors and uncertainties may be relevant in analysis. Qualitative comments might include, but are not limited to, parallax error in reading a scale, reaction time in starting and stopping a timer, random fluctuation in the read-out of a voltmeter, or difficulties in knowing just when a moving ball passes a given point.

Students should do their best to quantify these errors. For example, one student measured a voltage from an unstable power supply and wrote the following qualitative and quantitative comments.

> The voltage varied slightly over time; it went up and down by several hundredths of a volt. Therefore, the values recorded have an uncertainty greater than the least significant digit of each measurement. The uncertainty was estimated to be more like ±0.04 V.

Students can make statements about the minimum uncertainty in raw data based on the least significant figure in a measurement, and they can make statements about the manufacturer's claim of accuracy.

If uncertainties are small enough to be ignored, the student should note this fact. In addition, students can make educated guesses about uncertainties depending on the method of measurement.

In physics internal assessment, it is not specified which convention is preferred and a moderator will accept any convention in which the recorded uncertainties are of a sensible and consistent magnitude. It is good practice to write a short statement justifying the chosen uncertainty in each quantity.

The following examples are taken from an experiment to measure the current through and potential difference across a resistor.

Example 1

Students need to present raw data in a clear and comprehensible way, including the names of the quantities, the symbols and units, and an estimated raw uncertainty for each raw data quantity (table 1). Uncertainties are always relevant in raw data, even if they are small enough to ignore.

Voltage V / V $\Delta V \approx 0$ V	**Current I / mA** $\Delta I = \pm 0.3$ mA
1.00	0.9
2.00	2.1
3.00	2.8
4.00	4.1
5.00	5.0
6.00	5.9
7.00	7.1
8.00	8.0
9.00	8.9
10.0	9.9

Table 1

For internal assessment, this could contribute to the attainment of a high level in the analysis criterion.

Example 2

In this example (table 2) the uncertainty in the current is too small relative to the precision of the recorded data, although all other aspects are well presented.

Voltage V / V $\Delta V \approx 0$ V	**Current I / mA** $\Delta I = \pm 0.005$ mA
1.00	0.9
2.00	2.1
3.00	2.8
4.00	4.1
5.00	5.0
6.00	5.9
7.00	7.1
8.00	8.0
9.00	8.9
10.0	9.9

Table 2

For internal assessment, this could contribute to the attainment of a medium level in the analysis criterion.

Example 3

In this example (table 3) the student records raw data appropriately in a table, but the symbols are not given, there are no estimated uncertainties and the raw data is recorded with an inconsistent number of significant figures.

Voltage / V	**Current / mA**

1	0.9
2	2.1
3	2.8
4	4.1
5	5
6	5.9
7	7.1
8	8
9	8.9
10	9.9

Table 3

For internal assessment, this could contribute to the attainment of a medium level in the analysis criterion.

Example 4

In this example (table 4) the student has not included any units.

Voltage $\Delta V \approx 0$	**Current** $\Delta I = \pm 0.05$
1.00	0.90
2.00	2.10
3.00	2.80
4.00	4.10
5.00	5.00
6.00	5.90
7.00	7.10
8.00	8.00
9.00	8.90
10.0	9.90

Table 4

For internal assessment, this could contribute to the attainment of a medium level in the analysis criterion.

Example 5

The student may not record any raw data or the presentation and details may be incomprehensible, as in this example (table 5).

Raw Data: Voltage and Current

1 @ 0.9, 2 @ 2.1, 3 @ 2.8, 4 @ 4.1, 5 @ 5, 6 @ 5.9, 7 @ 7.1, 8 @ 8, 9 @ 8.9,10 @ 9.9

Table 5

For internal assessment, this could contribute to the attainment of a low level in the analysis criterion.

Processing data

Repeated measurements allow for calculation of the mean value with associated uncertainty for a quantity. Repeated measurements are used to reduce random errors.

The following examples are taken from an experiment to measure the time it takes for a ball to roll down an inclined plane.

Example 6

The student finds the average of three trial measurements of the time it takes for a ball to roll down a 1.00 m inclined plane (table 6). The student clearly and correctly calculates the average time.

Distance s / m $\Delta s \approx \pm 0.01$ **m**	**Time t / s** $\Delta t = \pm 0.01$ **s**	**Average time $\bar{t}$ / s** $\Delta \bar{t} = \pm 0.06$ **s**
1.00	6.28 6.39 6.31	6.33

Table 6

$$\bar{t} = \frac{t_1+t_2+t_3}{3} = \frac{(6.28+6.39+6.31)}{3} \approx 6.33 \text{ s}$$

$$\bar{t} = \frac{\text{range}}{2} = \frac{t_{max}-t_{min}}{2} = \frac{(6.39-6.28)}{2} \approx 0.06 \text{ s}$$

$$\bar{t} \pm \Delta\bar{t} = (6.33 \pm 0.06)\text{s} = 6.63 \text{ s} \pm 1\%$$

Where $\bar{t}$ represents the mean value and $\Delta\bar{t}$ represents the uncertainty in the mean value.

Students may express uncertainties as absolute, fractional, or percentages.

For internal assessment, this could contribute to the attainment of a high level in the analysis criterion.

Propagating errors

Random errors in raw data feed through a calculation to give an error in the final calculated result. There is a range of protocols for **propagating errors**. A simple protocol is as follows.

Note: A common protocol is that the final total percentage uncertainty should be cited to no more than one significant figure if it is greater than or equal to 2% and to no more than two significant figures if it is less than 2%.

Students should be able to propagate uncertainties through calculations involving addition, subtraction, multiplication, division and raising to a power. They can calculate the uncertainty using the range of data in a repeated measurement. It is good practice to show an example of each type of calculation.

Error bars

All students are expected to construct, where relevant, error bars on graphs. In many cases, only one of the two axes will require such error bars. In other cases, uncertainties for both quantities may be too small to construct error bars. A brief comment by the student on why the error bars are not included is then expected. If there is a large amount of data, the student need only draw error bars for the smallest value datum point, the largest value datum point, and several data points between these extremes. Error bars can be expressed as absolute values or percentages.

Arbitrary or made-up error bars will not earn the student credit. Students should be able to use the error bars to discuss, qualitatively, whether or not the plot is linear, and whether or not the two plotted quantities are in direct proportion. In respect of the latter, they should also be able to recognize if a systematic error is present. This is discussed later.

Using the error bars in a graph, students should be able to find the minimum and maximum gradients as well as the minimum and maximum intercepts, and then use these to express the overall uncertainty range in an experiment.

Processed data is usually understood as combining and manipulating raw data to determine the value of a physical quantity. Often raw data is multiplied or divided, added or subtracted from other values or constants. When this is done, errors and uncertainties should be propagated. However, there are cases where the raw data is appropriate for graphing and for establishing a conclusion. For example, in a motion experiment, position and time may be recorded and graphed. In such cases processing will be understood as transferring the data to an appropriate graph, constructing a best-fit line and determining the gradient. The processing of uncertainty consists of correctly constructing the relevant error bars on the graph and correctly determining the gradient and intercept of the graph with uncertainty.

When students process data by product or quotient, sum or difference, or some other mathematical function such as averaging, how well the student processes the raw data determines the mark awarded.

Example 7

The student calculates the square of the average time for three trial runs as shown above and also determines the uncertainty.

The average time and uncertainty is:

$$\bar{t} \pm \Delta\bar{t} = (6.33 \pm 0.06)\text{s}$$

The uncertainty in average time as a percentage:

$$\Delta\bar{t}\ \% = \frac{0.06}{6.33} \times 100 \approx 1\%$$

The average time squared is:

$$\bar{t}^2 = (6.33\ \text{s})^2 = 40.1\ \text{s}^2$$

The uncertainty in time squared is:

$$\Delta\bar{t}^2\ \% = 2 \times 1\% = 2\%$$

The average time squared and its uncertainty is thus:

$$\bar{t}^2 \pm \Delta\bar{t}^2\ \% = 40.1\ \text{s}^2 \pm 2\% = (40.1 \pm 0.8)\ \text{s}^2$$

The datum and its uncertainty are now correctly processed as an error bar on a graph of time squared against distance (figure 7).

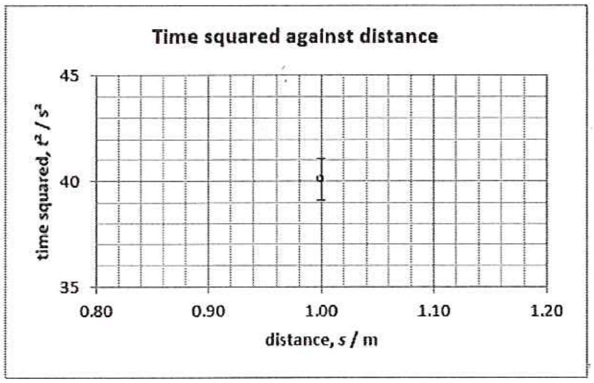

Figure 7

For internal assessment, this could contribute to the attainment of a high level in the analysis criterion.

Example 8

The student finds the average of three trial measurements of the time it takes for a ball to roll down a 1.00 m inclined plane but expresses the average with too many significant figures (table 7) and does not appreciate the propagation of uncertainty.

Distance s / m	**Time t / s** **$\Delta t = \pm 0.01$ s**	**Average time $\bar{t}$ / s** **$\Delta \bar{t} = \pm 0.01$ s**
1.00	6.28 6.39 6.31	6.3266

Table 7

The average time and its uncertainty are:

$$\bar{t} \pm \Delta \bar{t} = (6.3266 \pm 0.01)\ \mathrm{s}$$

Next the student calculates the square of the average time.

The average time squared is:

$$\bar{t}^2 = (6.3266\ \mathrm{s})^2 = 40.02586\ \mathrm{s}^2 \approx 40.03\ \mathrm{s}^2$$

The rounding was carried out to be consistent with the uncertainty in the raw data.

Then the student simply carries forward the raw data uncertainty, which is incorrect.

$$\bar{t}^2 \pm \Delta \bar{t}^2 = (40.03 \pm 0.01)\ \mathrm{s}^2$$

When this is graphed by the student the error bar is insignificant (figure 8), but this is a mistake due to incorrect processing of the uncertainty.

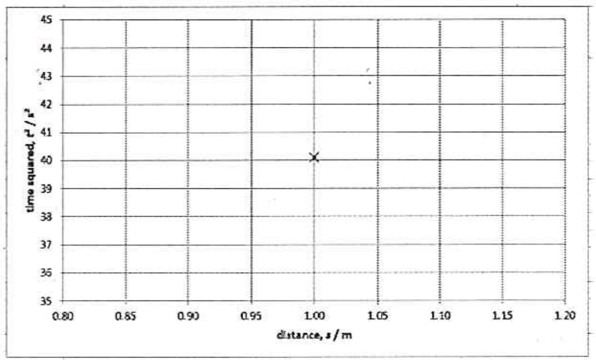

Figure 8

For internal assessment, this could contribute to the attainment of a medium level in the analysis criterion.

Example 9

The student could either fail to show any processing of data or process it incorrectly (table 8).

Distance s / m	Time t / s	Average time $\bar{t}$ / s
	6.28	
1.00	6.39	6.32666
	6.31	

Table 8

Next the student calculates (but incorrectly records) the square of the average time.

The average time squared is:

$$\bar{t}^2 = (6.32666\ \mathrm{s})^2 = 38.9439\ \mathrm{s}$$

There is a major error in the square of the average time and no uncertainties are appreciated.

For internal assessment, this could contribute to the attainment of a low level in the analysis criterion.

The final set of examples is taken from an experiment to determine the acceleration of free-fall by dropping a tennis ball from a range of different heights.

Example 10

In an experiment investigating acceleration of free fall of a tennis ball, the student constructs a graph (figure 9) of time squared, t^2, against the drop height, h, based on the data collected during the experiment (table 9). The student uses the gradient and uncertainties to determine the acceleration of free-fall with respective uncertainty.

Drop Height, h / m ±0.02	Mean time taken to fall, $\bar{t}$ / s	Uncertainty in the mean time $\Delta\bar{t}$ / s	% Uncertainty in the mean time $\Delta\bar{t}$ / %	Mean time squared, $\bar{t}^2$ / s²	% Uncertainty in the mean time squared $\Delta\bar{t}^2$ / %	Uncertainty in the mean time squared $\Delta\bar{t}^2$ / s²
2.00	0.43	0.03	7.3	0.18	14.7	0.03
3.00	0.68	0.03	4.6	0.47	9.2	0.04

4.30	0.86	0.04	5.2	0.74	10.4	0.08
4.80	0.93	0.03	3.4	0.86	6.8	0.06
6.30	1.14	0.04	3.9	1.30	7.8	0.10

Table 9

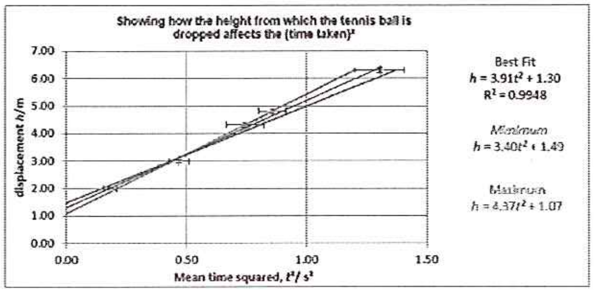

Figure 9

- Uncertainties can be rounded to one or two significant figures in accordance with the accepted protocol.
- The maximum and minimum lines have been drawn to pass through all of the error bars.

Gradient of line:

$$3.91 \pm \left(\frac{4.37-3.40}{2}\right) = (3.91 \pm 0.49)\ \mathrm{m\ s^{-2}} \approx (3.9 \pm 0.5)\ \mathrm{m\ s^{-2}} = 3.9\ \mathrm{m\ s^{-2}} \pm 13\%$$

Y-intercept:

$$1.30 \pm \left(\frac{1.49-1.07}{2}\right) = (1.30 \pm 0.21)\ \mathrm{m} \approx (1.3 \pm 0.2)\ \mathrm{m\ s^{-2}} = 1.3\ \mathrm{m} \pm 16\%$$

Starting with $s = ut + \frac{1}{2}at^2$ and considering the object is dropped from rest, then $u = 0$.

$$a = \frac{2s}{t^2} = 2\left(\frac{s}{t^2}\right) = 2 \times \text{gradient}$$

$$a = 2 \times (3.9 \pm 13\%) = 7.8 \pm 13\% = 7.8 \pm 1.0\ \mathrm{m\ s^{-2}}$$

In this experiment the acceleration of free-fall was determined to be $7.8 \pm 1.0\ \mathrm{m\ s^{-2}}$.

For internal assessment, this could contribute to the attainment of a high level in the analysis criterion.

Example 11

The same data is used, but this time the student has failed to determine maximum and minimum gradients using the uncertainties in time squared (figure 10). As a result he has not been able to determine the range and uncertainty in the calculated value of acceleration of free-fall.

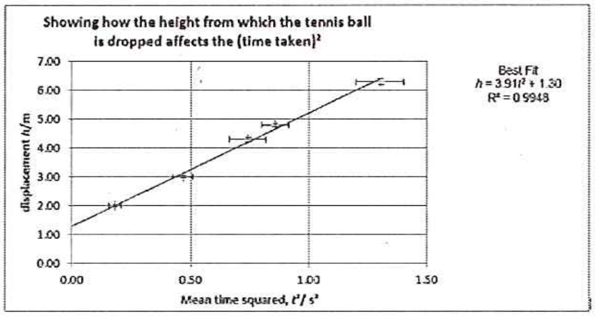

Figure 10

For internal assessment, this could contribute to the attainment of a medium level in the analysis criterion.

Example 12

The student has drawn an inappropriate graph with major errors (figure 11). The student has not included error bars or maximum and minimum lines. In addition, the student has drawn a line passing through the points rather than a line of best fit. This has not allowed for the gradient to be determined.

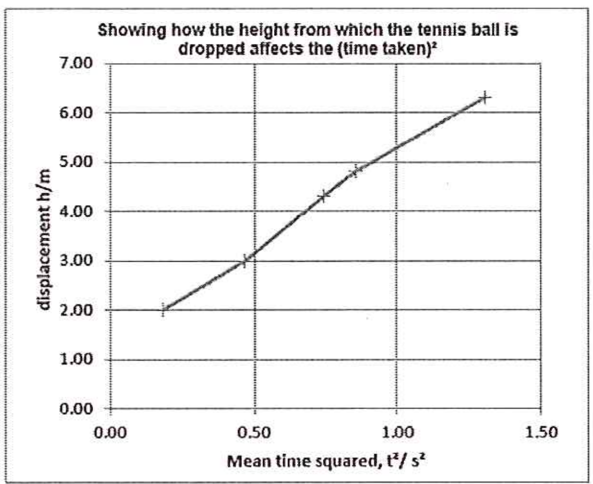

Figure 11

For internal assessment, this could contribute to the attainment of a low level in the analysis criterion.

Evaluation

- A detailed conclusion is described and justified which is entirely relevant to the research question and fully supported by the data presented.
- A conclusion is correctly described and justified through relevant comparison to the accepted scientific context.
- Strengths and weaknesses of the investigation, such as limitations of the data and sources of error, are discussed and provide evidence of a clear understanding of the methodological issues involved in establishing the conclusion.
- The student has discussed realistic and relevant suggestions for the improvement and extension of the investigation.

Errors and uncertainties are relevant in evaluation because students are expected to reach a reasonable and justified interpretation of the data and to appreciate the quality of the procedure, making clear reference to the types of error and to the measure of precision and accuracy.

Random and systematic error

Random errors arise from the imprecision of measurements and can lead to readings being above or below the "true" value. Random errors can be reduced with the use of more precise measuring equipment or its effect minimized through repeat measurements so that the random errors cancel out.

Systematic errors arise from a problem in the experimental set-up that results in the measured values always deviating from the "true" value in the same direction, that is, always higher or always lower. Examples of systematic error causes are miscalibration of a measuring device or friction in mechanics experiments. These are typically observed by a non-zero intercept on a graph when a proportional relationship is expected. Making repeat measurements will neither remove nor reduce the systematic error. The direction of any systematic errors should be appreciated.

Accuracy and precision

Accuracy is how close a measured value is to the expected value, whereas **precision** indicates how many significant figures there are in a measurement. For example, a mercury thermometer could measure the normal boiling temperature of water as 99.5°C (±0.5°C), while a data probe records it as 98.15°C (±0.05°C). In this case the mercury thermometer is more accurate whereas the data probe is more precise.

Impact of measurement uncertainty on the analysis and interpretation of processed data to deduce a conclusion

When attempting to measure an already known and accepted value of a physical quantity, such as the charge of an electron or the wavelength of a laser light, students need to appreciate whether or not the accepted value lies within the experimental value range.

- **The error in the measurement can be expressed by comparing the experimental value with the textbook or literature value.**

  For example, a student conducts Young's double-slit experiment and determines that the laser light wavelength is 610 nm. With experimental uncertainty, the student decides that $\lambda_{exp} \pm \Delta\lambda_{exp} = (6.1 \pm 0.2) \times 10^2$ nm. The manufacturer's literature that came with the laser gives a wavelength of $\lambda =$ 632.8 nm. The student might write the following.

  > The accepted value is 6.328×10^2 nm while my experimental value is $(6.1 \pm 0.2) \times 10^2$ nm. The accepted value lies just outside the experimental range, which is from 5.9×10^2 nm to 6.3×10^2 nm. My estimation of errors and uncertainties needs to be re-examined. Nonetheless, my results are close to the accepted value, about 4% too low. This sounds good, but if, in fact, the experimental uncertainty is only 2%, random errors alone cannot explain the difference, and some systematic error(s) must be present.

- **The experimental results fail to meet the accepted value.**

  The experimental range does not include the accepted value. The experimental value has an uncertainty of only 2%. A critical student would appreciate that they must have missed something here. There must be more uncertainty and/or errors than acknowledged.

Example 13

In example 10 given above, the acceleration of free-fall was determined to be $(7.8 \pm 1.0)\ \mathrm{m\ s^{-2}}$.

$$\text{Percentage uncertainty} = \frac{1.0}{7.8} \times 100\% = 13\%$$

Literature value of acceleration of free-fall = $9.81\ \mathrm{m\ s^{-2}}$ (IB *Physics data booklet*, (first assessment 2016))

$$\therefore\ \%\ \text{difference} = \frac{7.8-9.81}{9.81} \times 100\% = -20\%$$

The experimental range of the value of acceleration of free-fall lies between 6.8 and 8.8 m s^{-2} and this range does not include the literature value.

The fact that % difference > % uncertainty means random errors alone cannot explain the difference and some systematic error(s) must be present. This is also reflected in the fact that the line of best fit has a y-intercept of around 1.3 m.

This shows evidence of a large systematic error as well as large random errors.

Comments regarding a positive vertical shift or a negative horizontal shift in the data points can be discussed as part of the evaluation.

In addition to the above comments, students may also comment on errors in the assumptions of any theory being tested, and errors in the method and equipment being used. Typical examples may include the following.

- A graph of voltage against current does not form a linear and proportional line. It may be that the load resistance is changing as the current changes, so an ohmic relationship does not hold.
- Measuring the magnetic field alongside a current-carrying wire may confirm the inverse relationship, but for the smallest distances and the largest distances the data does not line up. The induction coil has a finite size, and the centre of it is assumed to be zero. This may not be the case. At large distances, the radius is similar in magnitude to the length of the wire, and the inverse law for the magnetic field assumed an infinite wire length.
- When using the motion detector, the software was not calibrated with the speed of sound first, and so the measured distances were inaccurate. This error was due to an unexamined assumption, but it was appreciated when the experimental results were evaluated.
- The experiment was done to determine the efficiency of an electric motor. As the investigation was carried out, the battery may have lost power. This would have affected the results.

Overall, students can critically appreciate limitations in their experimental results due to assumptions in the theory, in the experimental techniques and in the equipment used. Qualitative comments, based on a careful reading of graphed results, will guide students' criticism.

Evaluation of procedure and modifications

See exemplars in the "Assessed student work" section of the TSM.