Measurement terms

VCE Physics requires that students can distinguish between and apply the terms ‘accuracy’, ‘precision’, ‘repeatability’, ‘reproducibility’, and ‘validity’ when analysing their own and others’ investigation findings. An understanding of the terms ‘accuracy’ and ‘precision’ is also important in the analysis and discussion of investigations of a quantitative nature.

Accuracy

A measurement result is considered to be accurate if it is judged to be close to the ‘true’ value of the quantity being measured. The true value is the value (or range of values) that would be found if the quantity could be measured perfectly. For example, if an experiment is performed and it is determined that a given substance had a mass of 2.70 g, but the true value of mass is 3.20 g, then the measurement is not accurate since it is not close to the true value. The difference between a measured value and the true value is known as the ‘measurement error’.

‘Accuracy’ is not a quantity and therefore cannot be given a numerical value. It is allowable for a measurement to be described as being ‘more accurate’ when its method and/or instruments clearly reduce measurement error, such as using a triggered electronic timer system compared to a hand-operated stopwatch. Accuracy may not be quantified: ‘measurement error’ is the quantity used to evaluate how close a measured value is to the true value.

Precision

Experimental precision refers to how closely two or more measurement values agree with each other. A set of precise measurements will have very little spread about their mean value. For example, if a given substance was weighed five times, and a mass of 2.70 g was obtained each time, then the experimental data are precise. Precision gives no indication of how close the results are to the true value and is therefore a separate consideration to accuracy, so that if the true mass in the above example was 3.20 g then these data are precise but inaccurate.

Quantitatively, a measure of precision would be a measure of spread of measured values.

A measured mass of 2.7 g ± 0.1 g is less precise than 2.702 g ± 0.001 g.

Replication of procedures: repeatability and reproducibility

Experimental data and results must be more than one-off findings and should be repeatable and reproducible to draw reasonable conclusions. Repeatability refers to the closeness of agreement between independent results obtained with the same method on identical test material, under the same conditions (same operator, same apparatus and/or same laboratory). Reproducibility refers to the closeness of agreement between independent results obtained with the same method on identical test material but under different conditions (different operators, different apparatus and/or different laboratories). The purposes of reproducing experiments include checking of claimed precision and uncovering of any systematic errors that may affect accuracy from one or other experiments/groups. Experiments that use subjective human judgment/s or that involve small sample sizes or insufficient trials may also yield results that may not be repeatable and/or reproducible.

Validity
A measurement is 'valid' if it measures what it claims to be measuring. Both experimental design and the implementation should be considered when evaluating validity. Both experimental design and the implementation should be considered when evaluating validity. Data are said to be valid if the measurements that have been made are affected by a single independent variable only. They are not valid if the investigation is flawed and control variables have been allowed to change or there is observer bias.

Experimental uncertainty and error
It is important not to confuse the terms 'error' and 'uncertainty', which are not synonyms. It is also important not to confuse 'error' with 'mistake' or 'personal error'. Error, from a scientific measurement perspective, is the difference between the measured value and the true value of what is being measured. Uncertainty is a quantification of the doubt associated with a measurement result.
Experimental uncertainties are inherent in the measurement process and cannot be eliminated simply by repeating the experiment no matter how carefully it is done. There are two sources of experimental uncertainties: systematic effects and random effects. Experimental uncertainties are distinct from personal errors.
Personal errors
Personal errors include mistakes or miscalculations such as measuring a height when the depth should have been measured, or misreading the scale on a thermometer, or measuring the voltage across the wrong section of an electric circuit, or forgetting to divide the diameter by two before calculating the area of a circle using the formula $A = \pi r^2$. Personal errors can be eliminated by performing the experiment again correctly the next time, and do not form part of an analysis of uncertainties.
Systematic errors
Systematic errors are errors that affect the accuracy of a measurement. Systematic errors cause readings to differ from the true value by a consistent amount each time a measurement is made, so that all the readings are shifted in one direction from the true value. The accuracy of measurements subject to systematic errors cannot be improved by repeating those measurements.
Common sources of systematic errors include: faulty calibration of measuring instruments (and uncalibrated instruments) that consistently give the same inaccurate reading for the same value being measured), poorly maintained instruments (which may also have high random errors), or faulty reading of instruments by the user (for example, 'parallax error').
Random errors
Random errors affect the precision of a measurement and are always present in measurements (except for 'counting' measurements). These types of errors are unpredictable variations in the measurement process and result in a spread of readings.
Common sources of random errors are variations in estimating a quantity that lies between the graduations (lines) on a measuring instrument, the inability to read an instrument because the reading fluctuates during the measurement and making a quick judgment of a transient event, for example, the rebound height of a ball.
The effect of random errors can be reduced by making more or repeated measurements and calculating a new mean and/or by refining the measurement method or technique.

Outliers
Readings that lie a long way from other results are sometimes called outliers. Outliers should be further analysed and accounted for, rather than being automatically dismissed. Extra readings may be useful in further examining an outlier.

Quantitative analysis of uncertainty in measurement
Significant figures
Non-zero digits in data are always considered significant. Leading zeros are never significant whereas following zeros and zeros between non-zero digits are always significant. For example, 075.0210 contains six significant figures with the zero at the beginning not considered significant. A whole number may be a counting number or a measurement and determination of significant figures varies in the literature. For the purpose of the *VCE Physics Study Design*, whole numbers will have the same significant figures as number of digits, for example 400 has three significant figures while 400.0 has four.
Using a significant figures approach, one can infer the claimed accuracy of a value. For example, 400 is closer to 400 than 399 or 401. Similarly 0.0675 is closer to 0.0675 than 0.0674 or 0.0676.
Columns of data in tables should have the same number of decimal places, for example, measurements of lengths in centimetres or time intervals in seconds may yield the following data: 5.6, 9.2, 11.2 and 14.5. Significant figure rules should then be applied in subsequent data analysis.
Calculations in physics often involve numbers having different numbers of significant figures. In mathematical operations involving:

- addition and subtraction, the student should retain as many digits to the right of the decimal as in the number with the fewest significant digits to the right of the decimal, for example: 386.38 + 793.354 - 0.000397 = 1179.73
- multiplication and division, the student should retain as many significant digits as in the number with the fewest significant digits, for example: 326.95 x 10.2 ÷ 20.322 = 164.

Intermediate results in calculations should retain at least one significant figure more than such analysis suggests until the final result is ascertained.
Determining uncertainty in measured data
Whenever a measurement is made, there will always be uncertainty in the result obtained. Sources of variation in the data generated include contributions from both systematic and random effects. The uncertainty of a measurement can be expressed as the interval within which the true value can be expected to lie, with a given level of confidence or probability, for example, ‘the temperature is 20 °C ± 2°C,’. This is an uncertainty of 2 °C.
The uncertainty may sometimes be estimated by understanding the instruments used (for example, the uncertainty in reading a scale may be estimated as ± half the smallest scale division or the instrument specifications may state a nominal figure such as 2%) and considering the effect that any outside disturbances may have (for example, the temperature sensor is exposed to a flow of cool air from a nearby air conditioner).

When determining the average and uncertainty of a set of readings, the average is the simple mean (possibly with outliers ignored) while the uncertainty should be an estimate of the spread of readings.

Where several readings are averaged, the average should have the same number of decimal places as the uncertainty. For example, if the rebound heights of a basketball are measured to the nearest centimetre and yield the set of results: 60 ± 0.5, 62 ± 0.5, 59 ± 0.5, 60 ± 0.5, 61 ± 0.5, then the average rebound height is 60.4 cm with a maximum of 62 and a minimum of 59. The larger difference of these two values from the mean is 62 - 60 = 2 cm, so the reading now becomes 60.4 ± 2. Since the average has more decimal places than the uncertainty, the number recorded should be 60 ± 2 cm.

Propagation of uncertainty

There are various ways to represent uncertainty. For VCE Physics, students should represent uncertainties as absolute uncertainties, as in the preceding example of rebound height with $h = 60$ cm and $\Delta h = 2$ cm. Proportional uncertainties are sometimes used, expressed as a percentage, for example, $\Delta h/h = 2$ cm/ 60 cm = 0.033 or 3% (to 1 significant figure). Tables of results usually include absolute uncertainties.

When adding or subtracting quantities, these absolute uncertainties are added. Hence the difference between 62 ± 2 cm and 52 ± 2 cm is 10 ± 4 cm. When multiplying or dividing quantities, proportional uncertainties are added. This is more advanced and beyond the expectations of VCE Physics.

For any other mathematical treatment of variables, students may generally substitute the lowest and the highest data points to determine the range. An example of the uncertainty in the gradient of a linear trend line could be found by comparing the gradients of the steepest and least steep trend lines that could reasonably be fitted to the relevant data.