**MEASUREMENT**

All science is concerned with **measurement**. This fact requires that we have standards of measurement.

**Standards**

In order to make meaningful measurements in science we need standards of commonly measured quantities, such as those of mass, length and time. These standards are as follows:

1. The kilogram was once the mass of a cylinder of platinum-iridium alloy kept at the International Bureau of Weights and Measures in Paris.  In 2018, however, this standard was redefined in terms of the Planck constant, h, which has been measured with extraordinary precision in recent years. Its agreed value has been set as 6.62607015 × 10-34 kg m2 s–1, with researchers able to make precise mass measurement using equipment such as the Kibble balance (Watt balance). See link below for further information: [**New Definition of Kilogram**](https://physicsworld.com/a/new-definition-of-the-kilogram-comes-into-force/#:~:text=The%20kilogram%20is%20now%20defined,such%20as%20the%20Kibble%20balance.)
2. The metre is defined as the length of the path travelled by light in a vacuum during a time interval of 1/299 792 458 of a second. (Note that the effect of this definition is to fix the speed of light in a vacuum at exactly 299 792 458 ms-1).
3. The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom.

It is necessary for all such standards to be **constant, accessible and easily reproducible**.

**SI Units**

Scientists all over the world use the same system of units to measure physical quantities. This system is the International System of Units, universally abbreviated SI (from the French *Le Système International d'Unités*). This is the modern metric system of measurement. The SI was established in 1960 by the 11th General Conference on Weights and Measures (CGPM, *Conférence Générale des Poids et Mesures*). The CGPM is the international authority that ensures wide dissemination of the SI and modifies the SI as necessary to reflect the latest advances in science and technology.

Thus, the kilogram, metre and second are the SI units of mass, length and time respectively. They are abbreviated as kg, m and s. Various prefixes are used to help express the size of quantities – eg a nanometre = 10-9 of a metre; a gigametre = 109 metres. See the table of prefixes below.

|  |
| --- |
| **Table 1.  SI prefixes**  |
|

| **Factor** | **Name** | **Symbol** |
| --- | --- | --- |
| 1024 | yotta | Y |
| 1021 | zetta | Z |
| 1018 | exa | E |
| 1015 | peta | P |
| 1012 | tera | T |
| 109 | giga | G |
| 106 | mega | M |
| 103 | kilo | k |
| 102 | hecto | h |
| 101 | deka | da |

 |   |

| **Factor** | **Name** | **Symbol** |
| --- | --- | --- |
| 10-1 | deci | d |
| 10-2 | centi | c |
| 10-3 | milli | m |
| 10-6 | micro | µ |
| 10-9 | nano | n |
| 10-12 | pico | p |
| 10-15 | femto | f |
| 10-18 | atto | a |
| 10-21 | zepto | z |
| 10-24 | yocto | y |

 |
|  |

**Fundamental and Derived Quantities**

Physical quantities are not generally independent of one another. Many quantities can be expressed in terms of more fundamental quantities. The first three fundamental quantities we will deal with are those of mass, length and time. Many derived quantities can be expressed in terms of these three. For example, the derived quantity speed can be expressed as length/time.

Note that there are seven fundamental quantities in all. The other four are: current, thermodynamic temperature, amount of substance and luminous intensity. We will deal with these as we need them.

**Dimensions**

The expression of a derived quantity in terms of fundamental quantities is called the dimension of the derived quantity. The symbol M is used to denote the dimension of mass, as is L for length and T for time.

So, for example, to determine the dimensions of the derived quantity speed, we would look at the formula for speed, namely:

speed = distance/time

The dimensions of speed are then:

 [speed] = [distance] / [time] = L / T

where the square brackets are used to indicate that we are calculating the dimensions of whatever is inside the brackets.

Finally, we use our knowledge of indicies to simplify this epression.

 [speed] = LT-1

Question: Determine the dimensions of (a) area and (b) volume.

Answers: (a) L2 & (b) L3.

Dimensions can be used to check the correctness of an equation. The dimensions of the left hand side of the equation must equal the dimensions of the right hand side. Dimensions can also be used to verify that different mathematical expressions for a given quantity are equivalent.

Question: Given the formulas for the following derived quantities, calculate the dimensions of each quantity.

1. velocity = displacement/time
2. acceleration = change of velocity/time
3. momentum = mass x velocity
4. force = mass x acceleration
5. work = force x displacement

Answers: a. LT-1 b. LT-2 c. MLT-1 d. M LT-2 e. M L2T-2.

**Significant Figures**

Since the precision of all measuring instruments is limited, the number of digits that can be assumed as known for any measurement is also limited. When making a measurement, read the instrument to its smallest scale division. Estimate within a part of a division. The figures you write down for the measurement are called significant figures.

In Physics, if you write 3.0, you are stating that you were able to estimate the first decimal place of the quantity and you are implying an error of 0.05 units. If you just write 3, you are stating that you were unable to determine the first decimal place and you are implying an error of 0.5 units.

It is very important that you do not overstate the precision of a measurement or of a calculated quantity. **A calculated quantity cannot have more significant figures than the measurements or supplied data used in the calculation.** So, for example, if the length, breadth & height of a rectangular prism is each known to 2 significant figures, the volume calculated from these figures cannot have more than 2 significant figures. Let’s say the volume = 3.7cm x 2.9cm x 5.1cm = 54.723 cm3. You would state the volume as 55cm3 (2 significant figures only). Note that we have rounded the volume up to the nearest whole number in this case.

**Zeros**

* Zeros between the decimal point and the first non-zero digit **are not** significant. eg 0.00035 has 2 significant figures.
* Zeros that round off a large number **are not** significant. eg 35,000 has 2 significant figures.
* Zeros at the end of a string of decimals **are** significant. eg 0.5500 has 4 significant figures. The last 2 digits are meaningful here. The measurement is 0.5500 not 0.5501 or 0.5499.
* Zeros in between non-zero digits **are** significant. eg 0.7001 has 4 significant figures. The first zero is not significant but the next two are.

**Order & Scientific Notation**

The order of a number is the nearest power of 10 to that number. eg 166,000 has an order of 105; 756,000 has an order of 106; 0.099 has an order of 10-1.

In Physics quite often scientific notation is used. Write one non-zero figure before the decimal point and correct the magnitude of the number by using the appropriate power of ten. eg 166,000 can be written as 1.66 x 105; 0.099 can be written as 9.9 x 10-2.

**ACCURACY, RELIABILITY AND VALIDITY**

These three terms are often used when referring to experiments, experimental results and data sources in Science.  It is very important that students have a good understanding of the meaning and use of these terms.  The following notes under the blue headings were taken from **“Optimizing Student Engagement and Results in the Quanta to Quarks Option”** by Dr Mark Butler, Gosford High School.  I used to provide a link to the full article but unfortunately, the full article is no longer available online.

**a) ACCURACY: *Conformity to truth.***

Science texts refer to **accuracy** in two ways:

(i) **Accuracy** of a result or experimental procedure can refer to the percentage difference between the experimental result and the accepted value. The stated uncertainty in an experimental result should always be greater than this percentage accuracy.

(ii) **Accuracy** is also associated with the inherent uncertainty in a measurement. We can express the accuracy of a measurement explicitly by stating the estimated uncertainty or implicitly by the number of significant figures given. For example, we can measure a small distance with poor accuracy using a metre rule, or with much greater accuracy using a micrometer. Accurate measurements do not ensure an experiment is valid or reliable. For example consider an experiment for finding g in which the time for a piece of paper to fall once to the floor is measured very accurately. Clearly this experiment would not be valid or reliable (unless it was carried out in vacuum).

**b) RELIABILITY: *Trustworthy, dependable*.**

In terms of first hand investigations **reliability** can be defined as repeatability or consistency. If an experiment is repeated many times it will give identical results if it is reliable. In terms of second hand sources reliability refers to how trustworthy the source is. For example the NASA web site would be a more reliable source than a private web page. (This is not to say that all the data on the site is valid.) The reliability of a site can be assessed by comparing it to several other sites/sources.

**c) VALIDITY*: Derived correctly from premises already accepted, sound, supported by actual fact.***

A **valid** experiment is one that fairly tests the hypothesis. In a valid experiment all variables are kept constant apart from those being investigated, all systematic errors have been eliminated and random errors are reduced by taking the mean of multiple measurements. An experiment could produce reliable results but be invalid (for example Millikan consistently got the wrong value for the charge of the electron because he was working with the wrong coefficient of viscosity for air). An unreliable experiment must be inaccurate, and invalid as a valid scientific experiment would produce reliable results in multiple trials.

**NOTE - The notes that follow, on accuracy & precision, nature & use of errors and determination of errors are my own work.**

**ACCURACY & PRECISION**

Another term you will hear in relation to experiments and experimental results is the term **precision**.  Precision is the degree of exactness with which a quantity is measured.  It refers to the repeatability of the measurement.  The term precision is therefore interchangeable with the term reliability.  The two terms mean the same thing but you will hear & read both in relation to science experiments & experimental results.

The precision of a measuring device is limited by the finest division on its scale.

Note too, that a highly precise measurement is not necessarily an accurate one.  As indicated in the first definition of accuracy above, **accuracy** is the extent to which a measured value agrees with the "true" or accepted value for a quantity.  In scientific experiments, we aim to obtain results that are both accurate and precise.  The section on **errors** below will hopefully further clarify the four important terms defined in these last two sections of notes - accuracy, reliability, precision & validity.

## NATURE AND USE OF ERRORS

**Errors** occur in all physical measurements.  When a measurement is used in a calculation, the error in the measurement is therefore carried through into the result.  The two different types of **error** that can occur in a measured value are:

**Systematic error** – this occurs to the same extent in each one of a series of measurements eg zero error, where for instance the needle of a voltmeter is not correctly adjusted to read zero when no voltage is present.

**Random error** – this occurs in any measurement as a result of variations in the measurement technique (eg parallax error, limit of reading, etc).

When we report errors in a measured quantity we give either the **absolute error**, which is the actual size of the error expressed in the appropriate units or the **relative error**, which is the absolute error expressed as a fraction of the actual measured quantity. Relative errors can also be expressed as **percentage errors**. So, for instance, we may have measured the acceleration due to gravity as 9.8 m/s2 and determined the error to be 0.2 m/s2. So, we say the **absolute error** in the result is 0.2 m/s2 and the **relative error** is 0.2 / 9.8 = 0.02 (or 2%). Note relative errors have no units. We would then say that our experimentally determined value for the acceleration due to gravity is in error by 2% and therefore lies somewhere between 9.8 – 0.2 = 9.6 m/s2 and 9.8 + 0.2 = 10.0 m/s2. So we write **g = 9.8** ± **0.2 m/s2**. Note that determination of errors is beyond the scope of the current course.

Consider three experimental determinations of **g**, the acceleration due to gravity.

**Experiment A** **Experiment B** **Experiment C**

**8.34 ± 0.05 m/s2 9.8 ± 0.2 m/s2 3.5 ± 2.5 m/s2**

**8.34 ± 0.6% 9.8 ± 2% 3.5 ± 71%**

We can say that **Experiment A** is more **reliable** (or **precise**) than **Experiment B** because its relative error is smaller and therefore if the experiment was repeated we would be likely to get a value for **g** which is very close to the one already obtained. That is, **Experiment A** has results that are very **repeatable (reproducible)**. **Experiment B**, however, is much more **accurate** than **Experiment A**, since its value of **g** is much **closer to the accepted value**. Clearly, **Experiment C** is neither accurate nor reliable.

In terms of **validity**, we could say that **Experiment B** is quite valid since its result is very accurate and reasonably reliable – repeating the experiment would obtain reasonably similar results. **Experiment A** is not valid, since its result is inaccurate and **Experiment C** is invalid since it is both inaccurate and unreliable.

How do you **improve the reliability** of an experiment? Clearly, you need to make the experimental results highly reproducible. You need to **reduce the relative error** (or spread) in the results as much as possible. To do this you must reduce the **random errors** by: (i) using appropriate measuring instruments in the correct manner (eg use a micrometer screw gauge rather than a metre ruler to measure the diameter of a small ball bearing); and (ii) taking the mean of multiple measurements.

To **improve the accuracy and validity** of an experiment you need to keep all variables constant other than those being investigated, you must eliminate all systematic errors by careful planning and performance of the experiment and you must reduce random errors as much as possible by taking the mean of multiple measurements.

**DETERMINATION OF ERRORS**

All experimental science involves the measurement of quantities and the reporting of those measurements to other people. We have already seen that stating the absolute and relative errors in our measurements allows people to decide the degree to which our experimental results are reliable. This in turn helps people to decide whether our results are valid or not.

Clearly then it is important for all scientists to understand the nature and sources of errors and to understand how to calculate errors in quantities. A whole branch of mathematics has been devoted to error theory. Methods exist to estimate the size of the error in a result, calculated from any number of measurements, using any combination of mathematical operations. We will investigate a few of these methods appropriate for high school Physics courses.

**Experimental Errors**

As mentioned previously, variations will occur in any series of measurements taken with a suitably sensitive measuring instrument. The variations in different readings of a measurement are usually referred to as **“experimental errors”**. They are not to be confused with “mistakes”. Such variations are normal.

**Accounting for Random Errors**

Let’s say we use a micrometer screw gauge to measure the diameter of a piece of copper wire. The micrometer allows us to read down to 0.01mm. We may obtain a set of readings in mm such as: 0.73, 0.71, 0.75, 0.71, 0.70, 0.72, 0.74, 0.73, 0.71 and 0.73.

The variation in these figures is probably mainly due to the fact that the wire is not of uniform diameter along its length. However, the variation could also be caused by slight variations in the measuring technique – closing the jaws of the micrometer more or less tightly from one measurement to the next. The experimenter may have occasionally read the scale at an angle other than perpendicular to the scale, thus introducing parallax error into the results. Such factors as these cause random variations in the measurements and are therefore called **Random Errors**. The question we must ask is: How do we take account of the effects of random errors in analysing and reporting our experimental results?

**Distribution Curves**

If we had taken say 50 readings of the diameter of the wire instead of just 10, we could use our knowledge of Statistics to draw a frequency histogram of our measurements, showing the number of times each particular value occurs. This would be very helpful to anyone reading our results since at a glance they could then see the nature of the distribution of our readings. If the number of readings we take is very high, so that a fine subdivision of the scale of readings can be made, the histogram approaches a continuous curve and this is called a **distribution curve**.

If the errors are truly random, the particular distribution curve we will get is the bell-shaped Normal (or Gaussian) Distribution shown below.

The readings or measured values of a quantity lie along the x-axis and the frequencies (number of occurrences) of the measured values lie along the y-axis. The Normal Curve is a smooth, continuous curve and is symmetrical about a central “x” value. The peak in frequency occurs at this central x value.

The basic idea here is that if we could make an infinite number of readings of a quantity and graph the frequencies of readings versus the readings themselves, random errors would produce as many readings above the “actual” or “true” value of the quantity as below the “true” value and the graph that we would end up with is the Normal Curve. The value that occurs at the centre of the Normal Curve, called the mean of the normal distribution, can then be taken as a very good estimate of the “true” value of a measured quantity.

So, we can start to answer the question we asked above. The effect of random errors on a measurement of a quantity can be largely nullified by taking a large number of readings and finding their mean.

 

Examine the set of micrometer readings we had for the diameter of the copper wire. Let us calculate their mean, the deviation of each reading from the mean and the squares of the deviations from the mean.

Reading Deviation Squares of Deviations

x (mm) From Mean From Mean

0.73 + 0.01 0.0001

0.71 - 0.01 0.0001

0.75 + 0.03 0.0009

0.71 - 0.01 0.0001

0.70 - 0.02 0.0004

0.72 0.00 0.0000

0.74 + 0.02 0.0004

0.73 + 0.01 0.0001

0.71 - 0.01 0.0001

0.73 + 0.01 0.0001

For the moment, we will only be interested in the first two columns above. A glance at the deviations shows the random nature of the scattering.

The formula for the mean yields:

 

The mean is calculated as 0.723 mm but since there are only two significant figures in the readings, we can only allow two significant figures in the mean. So, the mean is 0.72 mm. Once we have the mean, we can calculate the figures in the 2nd column of the Table above. These are the deviation of each reading from the mean.

We can use the maximum deviation from the mean, 0.03 mm, as the **“maximum probable error (MPE)”** in the diameter measurements. So, we can state the diameter of the copper wire as **0.72 ± 0.03 mm** (a 4% error). This means that the diameter lies between 0.69 mm and 0.75mm.

An interesting thought occurs: What if all the readings of the diameter of the wire had worked out to be the same? What would we use as an estimate of the error then?

In that case, we would look at the **limit of reading** of the measuring instrument and use half of that limit as an estimate of the probable error. So, as stated above, our micrometer screw gauge had a limit of reading of 0.01mm. Half the limit of reading is therefore 0.005mm. The diameter would then be reported as 0.72 ± 0.005 mm (a 0.7% error). This means that the diameter lies between 0.715 mm and 0.725 mm. Note that we still only quote a maximum of two significant figures in reporting the diameter.

It is also worth emphasizing that in the stated value of any measurement only the last digit should be subject to error. For example, you would not state the diameter of the wire above as 0.723 ± 0.030 mm because the error is in the 2nd decimal place. This makes the 3rd decimal place meaningless. If you do not know the 2nd decimal place for certain, there is no point stating a 3rd decimal place in the value of the quantity.

We can now complete our answer to the question: **How do we take account of the effects of random errors in analysing and reporting our experimental results?** At high school level, it is sufficient to:

* Take a large number of readings – at least 10, where time and practicality permit.
* Calculate the mean of the readings as a reasonable estimate of the “true” value of the quantity.
* Use the largest deviation of any of the readings from the mean as the maximum probable error in the mean value.
* If all the readings are the same, use half the limit of reading of the measuring instrument as the MPE in the result.

**Standard Deviation**

Now, for those who would like to go a little further in error theory, we can turn our attention to the third column of figures in the Table above. These figures are the squares of the deviations from the mean. Without going into any theoretical explanation, it is common practice for scientists to use a quantity called the **sample standard deviation** of a set of readings as an estimate of the error in a measured quantity. The standard deviation, lower case sigma), is calculated from the squares of the deviations from the mean using the following formula:

 

From the 3rd column above we have

 

And n (the number of readings) = 10

Therefore, 

We could therefore report the diameter of the copper wire as 0.72 ± 0.016 mm (a 2% error). This means that the diameter lies between 0.704 mm and 0.736 mm. Note that we still only quote a maximum of two significant figures in reporting the diameter.

Why do scientists use standard deviation as an estimate of the error in a measured quantity? Well, the standard deviation of a set of experimental data is a reliable statistical measure of the variability or spread of the data from the mean. A high standard deviation indicates that the data is spread out over a large range of values, whereas a low standard deviation indicates that the data values tend to be very close to the mean.

Also, standard deviation gives us a measure of the percentage of data values that lie within set distances from the mean. If a data distribution is approximately normal then about 68% of the data values are within 1 standard deviation of the mean (mathematically, μ ± σ, where μ is the arithmetic mean), about 95% are within two standard deviations (μ ± 2σ), and about 99.7% lie within 3 standard deviations (μ ± 3σ). So, when we quote the standard deviation as an estimate of the error in a measured quantity, we know that our error range around our mean (“true”) value covers the majority of our data values. In other words, it can give us a level of confidence in our error estimate. If you wish, you could quote the error estimate as two standard deviations.

**Accounting for Systematic Errors**

Systematic errors are errors which occur to the same extent in each one of a series of measurements. Causes of systematic error include:

* Using the instrument wrongly on a consistent basis. A simple example is parallax error, where you view the scale of a measuring instrument at an angle rather than from directly in front of it (ie perpendicular to it). A person sitting in the passenger seat of a car for instance may glance at the speedometer and think the driver is going above the speed limit by a couple of km/hr, when in fact the driver, sitting directly in front of the speedometer, can see that the speed of the car is right on the speed limit.
* The instrument may have a built-in error. A simple example is zero error, where the instrument has not been correctly set to zero before commencing the measuring procedure. An ammeter for instance may show a reading of 0.2A when no current is flowing. So, as you use the instrument to measure various currents each of your measurements will be in error by 0.2A. The ammeter needle should have been reset to zero by using the adjusting screw before the measuring started.
* External conditions can introduce systematic errors. A metal rule calibrated for use at 25oC will only be accurate at that temperature. If you use this rule say at 5oC it will produce readings that are consistently larger than they should be since at the lower temperature the metal will have contracted and the distance between each scale division will be smaller than it should be. Knowing the expansion coefficient of the metal would allow the experimenter to correct for this error.

**Systematic errors can drastically affect the accuracy of a set of measurements.** Unfortunately, systematic errors often remain hidden. Clearly, to reduce the incidence of systematic errors the experimenter must:

* Use all measuring instruments correctly and under the appropriate conditions.
* Check for zero error. This can include performing test measurements where a standard or known quantity is measured to ensure that the instrument is giving accurate results. For example, a thermometer could be checked at the temperatures of melting ice and steam at 1 atmosphere pressure.

**Errors in Calculated Quantities**

In scientific experiments, we often use the measured values of quantities to calculate some new quantity. The error in the new quantity depends on the errors in the measured values used to calculate it.

**Addition & Subtraction**

When two (or more) quantities are added or subtracted to calculate a new quantity, we add the maximum probable errors in each quantity to obtain the maximum probable error in the new quantity.

Eg When heating water we may measure the starting temperature to be (35.0 ± 0.5)oC and the final temperature to be (85 ± 0.5)oC. The change in temperature is therefore (85 – 35)oC ± (0.5+0.5)oC or 50 ± 1.0oC. Note that we add the MPE’s in the measurements to obtain the MPE in the result.

**Multiplication & Division**

When two (or more) quantities are multiplied or divided to calculate a new quantity, we add the percentage errors in each quantity to obtain the percentage error in the new quantity.

Eg Let us assume we are to determine the volume of a spherical ball bearing. After performing a series of measurements of the radius using a micrometer screw gauge, the mean value of the radius is found to be 9.53mm ± 0.05mm. Thus, the percentage error in the radius is 0.5%. [ % error = (0.05/9.53) x 100 ]

The formula for the volume of a sphere is V = 4/3 π r3. Using this formula, the value for the volume of the ball bearing is found to be 3625.50mm3.

Note that the only measured quantity used in this calculation is the radius but it appears raised to the power of 3. The formula is really V = 4/3 π r x r x r.

So, % error in volume = % error in r + % error in r + % error in r

Therefore, % error in volume = 0.5% + 0.5% + 0.5% = 1.5%

The volume of the ball bearing is therefore 3625.50mm3 ± 1.5% or 3625.50mm3 ± 54.38mm3.

Now we look at the number of significant figures to check that we have not overstated our level of precision. There are only 3 significant figures in the radius measurement. We should therefore have only 3 significant figures in the volume. Writing the volume figure in more appropriate units achieves this nicely.

Changing mm3 to cm3, we have that the volume of the ball bearing is 3.63 ± 0.05cm3.

**Rejection of Readings**

**When is it OK to reject measurements from your experimental results?** This is a contentious question. There are many empirical rules that have been set up to help decide when to reject observed measurements. In the end, however, the decision should always come down to the personal judgement of the experimenter (1) and then only after careful consideration of the situation.

Where an actual mistake is made by the experimenter in taking a measurement or the measuring instrument malfunctions and this is noticed at the time, the measurement can be discarded. A record of the fact that the measurement was discarded and an explanation of why it was done should be recorded by the experimenter.

There may be other situations that arise where an experimenter believes he/she has grounds to reject a measurement. For instance, if we make 50 observations which cluster within 1% of the mean and then we obtain a reading which lies at a separation of 10%, we would be fairly safe in assuming that this reading was caused by some sort of mistake on the part of the experimenter or a failure of the measuring instrument. We would be fairly safe in rejecting this measurement from our results. (1)

The necessity is to build up confidence in the main set of measurements before feeling justified in doing any rejecting. Thus, there is no justification for taking two readings and then rejecting the third because it is vastly different to the first two. Unless the situation is absolutely clear cut it is by far the best to retain all the readings whether you like them or not. (1)

We always do well to remember that many of the greatest discoveries in Physics have taken the form of outlying measurements. (1)

**Reference:**

1. Baird, D.C. (1962). “Experimentation: An Introduction To Measurement Theory And Experiment Design”, Prentice-Hall Inc, New Jersey

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