2023

PapaCambridge

Physical Quantities and Units

[Unit 1]

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Physical Quantities

A physical quantity is a feature of something that can be measured and every physical quantity has a numerical value and a unit.

Examples of these include quantities such as time, mass, length, speed, and temperature.

SI Quantities & Base Units

The SI system of units is founded upon seven fundamental or base units and is based on the metric system of measurement and is used by scientists around the world.

The 7 base units are the following:

Base Quantity	Base Unit	Symbol
Mass	Kilogram	kg
Length	Meter	M
Time	Second	S
Electric Current	Ampere (Amp)	A
Temperature	Kelvin	K
Amount of substance	Mole	Mol
Luminous Intensity	Candela	Cd

The Prefixes

All quantities have one unit, this unit can have multiples and sub-multiples so that the unit can be used for values of different sizes.

Here are some prefixes which you should know:

Prefix	Symbol	Multiplier	Prefix	Symbol	Multiplier
Tera	T	10^{12}	Centi	c	10^{-2}
Giga	G	10^{9}	Milli	m	10^{-3}
Mega	M	10^{6}	Micro	µ	10^{-6}
Kilo	K	10^{3}	Nano	n	10^{-9}
Deci	d	10^{-1}	Pico	p	10^{-12}

Derived Units

These units are basically a combination of the base units.

Derived units may have their own units but can also be expressed in base units.

Quantities without any named unit (such as the moment of a force) are expressed in terms of other units (like Nm or kgm^2s^{-2}).

Quantity	Unit	Derived Unit	Quantity	Unit	Derived Unit
Frequency	Hertz	s^{-1}	Energy	J	$kg\ m^2\ s^{-2}$
Velocity	ms^{-1}	$m\ s^{-1}$	Power	W	$kg\ m^2\ s^{-3}$
Acceleration	ms^{-2}	$m\ s^{-2}$	Electric Charge	C	A s
Force	N	$kg\ ms^{-2}$	Potential Difference	V	$kg\ m^2\ s^{-3}\ A^{-1}$
Momentum	Ns	$kg\ ms^{-1}$	Electrical Resistance	Ω	$kg\ m^2\ s^{-3}\ A^{-2}$

Homogeneity of Equations

Equations are homogenous when both sides have the same units meaning that there are no errors in it.

Example:

The drag force F acting on a sky diver is given by the equation:

$$F = \frac{1}{2} C\rho A v^2$$

Where C is a constant, ρ is the density of air, A is the cross-sectional area of the diver and v is the speed of fall.

Show that C has no base units.

First, let us note down the base units of the known quantities:

Quantity	Unit	Quantity	Unit
A	m^2	v	ms^{-1}
ρ	kgm^{-3}	F	$kgms^{-2}$

Now, multiply these units together (or whatever the equation does):

$$\text{kgms}^{-2} = \frac{1}{2} \times C \times \text{kgm}^{-3} \times \text{m}^2 \times (\text{ms}^{-1})^2$$

$$\text{kgms}^{-2} = \frac{1}{2} \times C \times \text{kgm}^{-3} \times \text{m}^2 \times \text{ms}^{-2}$$

$$\text{kgms}^{-2} = \frac{1}{2} \times C \times \text{kgms}^{-2}$$

Since both sides have the same units, we can say that C has no unit.

We don’t consider ½ because it does not change the units at all.

The Problem

As we know, homogenic equations only have the same units.
This does not necessarily mean that the equation is error-free.

This is because the error may not be the units but the equation itself, such as specific number.

Conventions for Symbols & Units

When writing the units on a graph axis or table header, we usually write it in this format:

symbol/unit

Here, we write the symbol in italics (like t or v) and the unit in roman which is separated by a slash.

Errors & Uncertainties

Absolute, Percentage, and Fractional Uncertainty

Uncertainty refers to the total range of values within which a measurement is likely to lie in.

Absolute uncertainty is the size of the range of values within which the 'true value' of a measurement is likely to lie

Percentage uncertainty is the ratio of the absolute uncertainty in a measurement to the measured value, expressed as a percentage.

Fractional uncertainty is the ratio of the absolute uncertainty in a measurement to the measured value, expressed as a fraction.

For Example:

Let's say a measurement was 46.0 ± 0.5cm.

The absolute uncertainty of this is ± 0.5cm.

The percentage uncertainty is ± 1% and is calculated like so:

$$\frac{0.5}{46} \times 100 \approx 1\%$$

The fractional uncertainty is literally:

$$\frac{0.5}{46} = \frac{1}{92}$$

A Few Rules:

1. When writing measurements, the number of significant figures of the measurement indicates its uncertainty.
2. The uncertainty in a measurement should be stated to 1 significant figure.
3. The value for the quantity should be stated to the same number of decimal places as the uncertainty.
4. Uncertainty ≠ Error (usually).

Accuracy & Precision

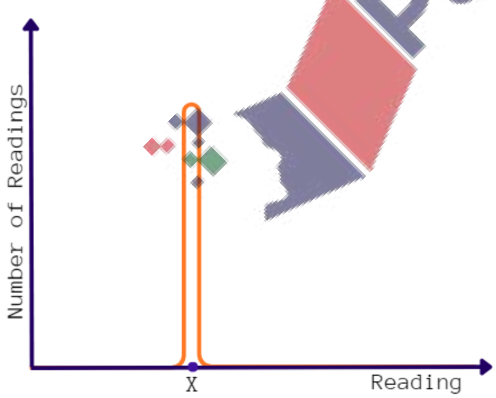
Accuracy	Precision
Refers to the closeness of a measured value to the "true" or "known" value.	Refers to how close a set of measured values are to each other.
Depends on: ▪ Equipment used ▪ Skill of the experimenter ▪ Technique(s) used	**Depends on:** ▪ Size of the range of values ▪ Uncertainty in measurement

On The Graph

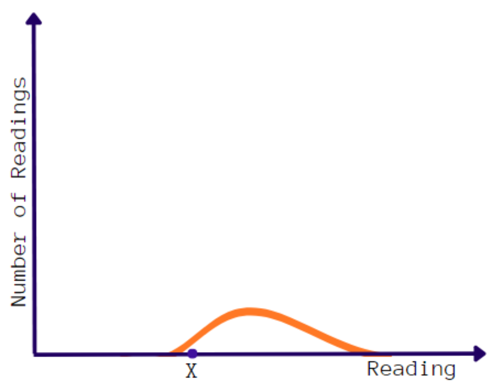
Let's put accuracy and precision in a visual to understand the difference.

Let's say the quantity we are measuring is called "X" and make a graph which records our readings, we will place the number of readings on the y-axis and the value on the x-axis.

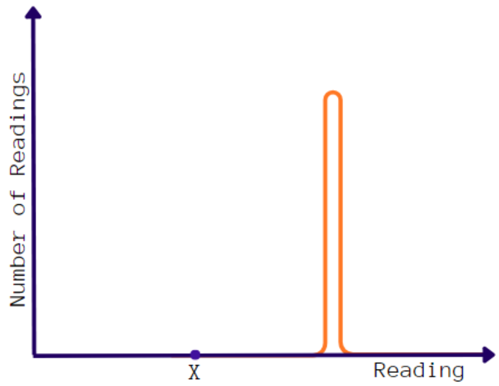
Accurate and Precise



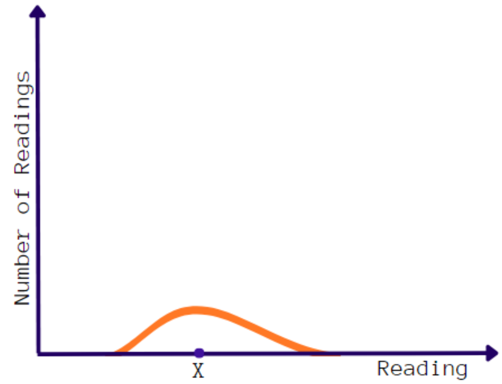
Not Accurate and Imprecise



Not Accurate but Precise



Accurate but Imprecise



In the graphs, when the readings are precise, they all have a large frequency of readings in one area and when they are accurate, the readings are more close to the answer.

Choice of Instruments

The choice of an instrument for a measurement is related to the measurement being made.

For example, the diameter of a strand of hair would be measured using a micrometer screw gauge rather than a ruler.

Note: *This is likely to be examined when planning experiments*

Systematic & Random Error

Apart from the instruments themselves, we must also take the techniques of measuring into account as they can both; increase or decrease the uncertainty.

What is an Error?

Systematic Error

A systematic error is when the error results in the **reading being more than or less than the true value**, this shift is by a **fixed value** and in the **same direction** each time the measurement is taken.

Examples

Zero Error on an Instrument:

This is when the scale reading is not 0 before the measurements are taken; this is easily avoided by checking for the zero error before taking the measurements.

Reaction Times:

This is mainly to do with time because as humans, we have a small delay when starting or stopping a timer which causes delay and may lead to some incorrect values.

Note: *Systematic errors may be any error but it should lead to the measurement being off by the same amount.* ***(Don't trust me on this; I'm also just a student)***

Wrongly Calibrated Scale:

Usually, measurement tools are calibrated properly (no systematic error) making it unnecessary to check the calibration of tools in experiments.

Checking the calibration changes from tool to tool, for example, we can check a meter rule by placing many side by side or thermometers can be put in well-stirred water.

Random Error

This is due to the scatter of readings around the true value and can be reduced in 2 ways:

1. Plot a graph with all the values taken and draw a line of best fit.
2. Take an average of all the readings.

Examples

- Reading a ruler may cause errors such as the parallax error which may cause measurement(s) to be scattered.
- Taking readings which vary with time may cause some varying results as it is hard to read 2 scales at the same time.

Note: *Most of the examples were just errors made by us.*

Combining Uncertainties

When we obtain the value of a physical quantity, it is likely that we had to measure many other quantities to calculate it.

Each of these "other quantities" had an uncertainty of some sort in their value and so, we must combine these uncertainty values to get the uncertainty of our newly calculated quantity.

The 3 (Hopefully) Simple Rules

To combine uncertainties, we follow two simple rules:

1. For quantities which are added or subtracted to give a result, add the absolute certainties.
2. For quantities which are multiplied together or divided to give the result, add the fraction or percent uncertainties.
3. For quantities with indices, multiply the power by the percent uncertainty.

Examples

Example 1:

Let's say we have 2 lengths:

1. 5cm ± 0.1cm
2. 2cm ± 0.2cm

Now, let's find the difference between the 2 lengths:

$$5cm - 2cm = 3cm$$

Now to combine the uncertainties… just add them:

$$0.1 + 0.2 = 0.3cm$$

Therefore, the answer is **3cm ± 0.3cm.**

Example 2:

Let's say we need to divide 2 values:

1. 100m ± 20cm
2. 25s ± 0.5s

Now, let's divide the two:

$$\frac{100}{25} = 4ms^{-1}$$

To get the uncertainty, we add the fraction uncertainties:

$$\frac{0.2}{100} + \frac{0.5}{25} = \frac{0.2}{100} + \frac{2}{100} = \frac{2.2}{100} ms^{-1}$$

Therefore, the answer is $4ms^{-1}$ ± $0.022ms^{-1}$

Scalars and Vectors

A scalar quantity is a quantity which only has a magnitude and unit.

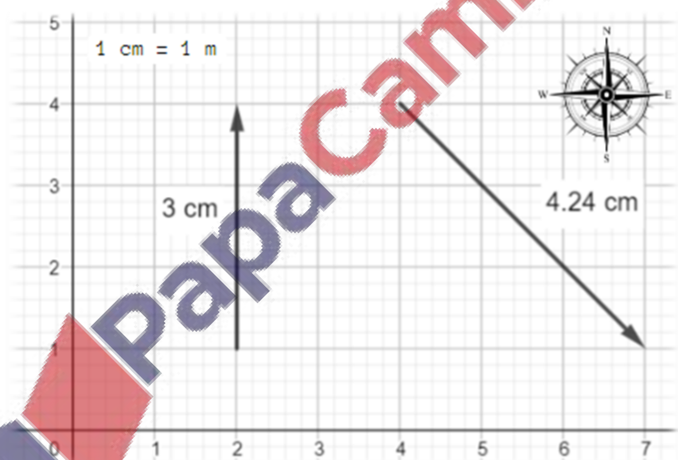
A vector quantity is a quantity with magnitude, unit, and a direction.

Examples

Quantity	Scalar	Vector	Quantity	Scalar	Vector
Momentum		✓	**Mass**	✓	
Weight		✓	**Speed**	✓	
Displacement		✓	**Power**	✓	
Velocity		✓	**Pressure**	✓	
Acceleration		✓	**Temperature**	✓	
Force		✓	**Density**	✓	

Representation of Vectors

One way of representing vectors is using arrows:

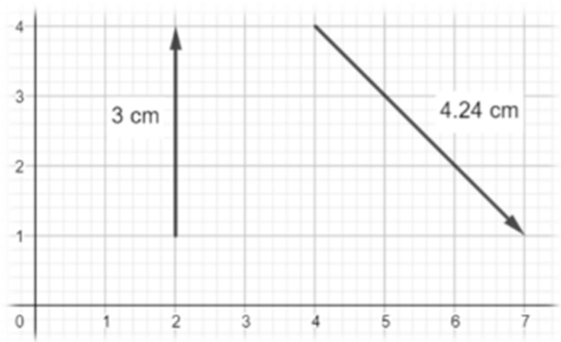


As seen in the image above, we can determine the following:

1. Arrow one shows a vector of 3 meters due north.
2. Arrow two shows a vector of 4.24 meters due south east.

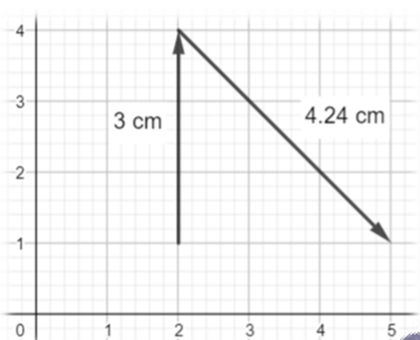
Vector Addition

Let us say we want to add 2 vectors:



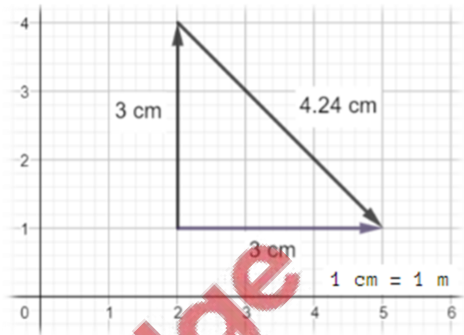
Step 1:

We take one of the vectors and place it on the top of the other so that they join:



Step 2:

Draw a new vector (the resultant vector) from the start of the trail to the end:



Step 3:

Convert the final measurement and write down the answer.

In this case it is a vector of 3 meters pointing in the east direction.

Resolving Vectors

As we know, we can add 2 vectors to get a resultant.

This resultant vector acts in the same way as any other vector.

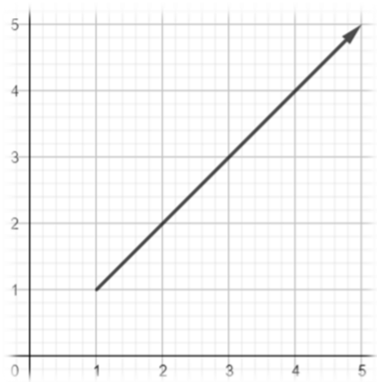
This means that we can "split up" a vector into two other vectors; this means that the vector is "resolved" into 2 "components".

The only condition for this is that when combined, the product of the components **MUST BE THE ORIGINAL VECTOR.**

Example

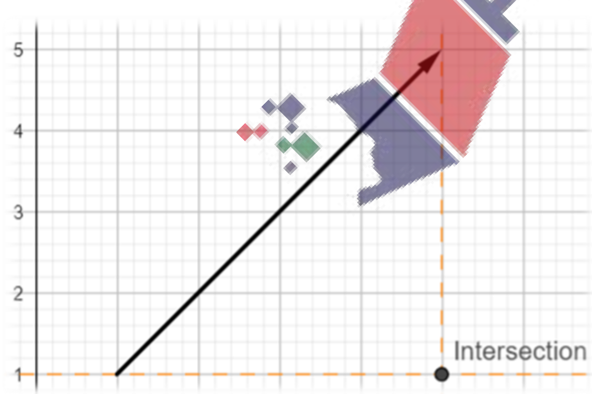
Question:

Let's say we wish to resolve the vector below:



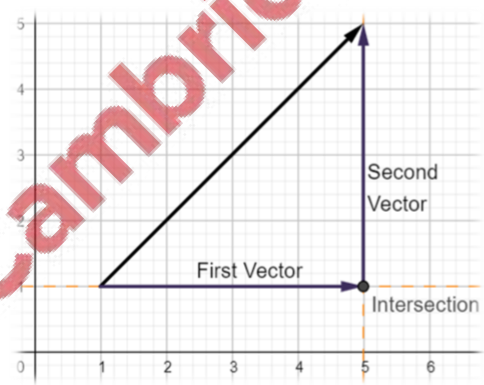
Step 1:

Make a line from both ends to make it so that they intersect:



Step 2:

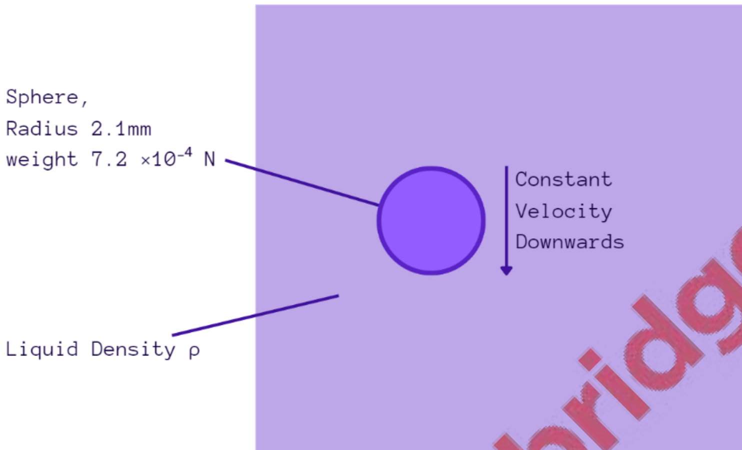
Make one vector from the end to the intersection point and another vector from the end of the first one:



Past Paper Questions

Question 1 [9702/22/F/M/22 Q1]

A sphere of radius 2.1mm falls with terminal (constant) velocity through a liquid, as shown in Fig. 1.1.



Three forces act on the moving sphere. The weight of the sphere is 7.2 × 10^{-4} N and the upthrust acting on it is 4.8 × 10^{-4} N. The viscous force F_V acting on the sphere is given by

$$F_V = krv$$

where r is the radius of the sphere, v is its velocity and k is a constant. The value of k in SI units is 17.

1. **Determine the SI base units of k.**

First up, rearrange the formula to get k:

$$k = \frac{F_V}{rv}$$

Now, replace the quantities with their SI units:

$$k = \frac{kgms^{-2}}{m \times ms^{-1}} = \frac{kgms^{-2}}{m^2s^{-1}} = kgms^{-2} \times m^{-2}s = \boldsymbol{kgm^{-1}s^{-1}}$$

The rest of the q is not related.

Question 2 [9702/23/M/J/20 Q1]

Part A:

State one similarity and one difference between distance and displacement

Similarity: They both have magnitude

Difference: Displacement has direction, distance does not.

Part B:

A student takes several measurements of the same quantity.

This set of measurements has high precision, but low accuracy.

Describe what is meant by:

High precision:

When the results fall in a small range.

Low accuracy:

When the results are not close to the true value.

Question 3 [9702/23/M/J/18 Q1 Part A]

An analogue voltmeter is used to take measurements of a constant potential difference across a resistor.

For these measurements, describe one example of:

1. **A systematic error:**

   Voltmeter scale not calibrated properly.

2. **A random error:**

   Reading the voltmeter incorrectly.

Question 4 [9702/13/M/J/15 Q2]

What is the joule (J) in SI base units?

A. $kgms^{-1}$ **B.** kgm^2s^{-1} **C.** $kgms^{-2}$ **D.** kgm^2s^{-2}

Use the formula for Work Done which has the unit joules:

$$W.D = Force \times Distance$$
$$W.D = kgms^{-2} \times m$$
$$W.D = \boldsymbol{kgm^2s^{-2}}$$

Question 5 [9702/22/O/N/17 Q1]

One end of a wire is connected to a fixed point. A load is attached to the other end so that the wire hangs vertically.

The diameter d of the wire and the load F are measured as

d = 0.40 ± 0.02mm,
F = 25.0 ± 0.5N.

Part A:

For the measurement of the diameter of the wire, state:

1. **The name of a suitable measuring instrument,**
   Micrometer screw gauge.
2. **How random errors may be reduced when using the instrument in (i).**
   Take many readings and get the average of the diameter.

Part B:

The stress σ in the wire is calculated by using the expression:

$$\boldsymbol{\sigma = \frac{4F}{\pi d^2}}$$

1. **Show that the value of σ is 1.99×10^8 Nm^{-2}.**

$$d = \frac{0.4}{10 \times 100} = 4 \times 10^{-4}\ m$$

$$\sigma = \frac{4 \times 25}{(4 \times 10^{-4})^2 \times \pi} \approx \mathbf{1.99 \times 10^8}$$

2. **Determine the percentage uncertainty in σ.**

   Find the percentage uncertainties:

   1. d = 5%
   2. F = 2%

   Now, create a basic formula using the 3 rules:

$$\%\sigma = \%F + (\%d \times 2)$$

   Now, substitute in the percent uncertainties:

$$\%\sigma = 2\% + (5\% \times 2) = \mathbf{12\%}$$

3. Use the information in (b)(i) and your answer in (b)(ii) to determine the value of σ, with its absolute uncertainty, to an appropriate number of significant figures.

First up, get 12% of the value of σ (absolute uncertainty):

$$1.99 \times 10^8 \times \frac{12}{100} = 2.388 \times 10^7$$

If you remember, we must round the absolute uncertainty to 1 s.f:

$$2.388 \times 10^7 \approx 2.0 \times 10^7$$

Now, round off the value of σ to match the d.p/s.f of absolute uncertainty:

$$1.99 \times 10^8 \approx 2 \times 10^8$$

Finally, put the absolute uncertainty and actual value together:

$$\mathbf{2 \times 10^8 \pm 2 \times 10^7 \; Nm^{-2}}$$

Question 6 [9702/12/M/J/15 Q2]

The average kinetic energy E of a gas molecule is given by the equation.

$$\boldsymbol{E = \frac{3}{2}kT}$$

Where T is the absolute (kelvin) temperature.

What are the SI base units of k?

A. $kg^{-1}m^{-1}s^2K$ **B.** $kg^{-1}m^{-2}s^2K$ **C.** $kgms^{-2}K^{-1}$ **D.** $kgm^2s^{-2}K^{-1}$

First, rearrange the formula for k:

$$E = 1.5 \times k \times T$$

$$k = \frac{E}{T \times 1.5}$$

We can remove the constant(s):

$$k = \frac{E}{T}$$

Replace the variables with SI units:

$$k = \frac{kgm^2s^{-2}}{K} = \boldsymbol{kgm^2s^{-2}K^{-1}}$$

Sources (and Resources) Used

Most of the information has come from the **AS & A Level Physics Student Book by Hodder Education**.

Other resources/tools have also been used and are listed below:

Name	Link	Use
Save My Exams	**LINK**	Mainly understanding concepts to make them simpler
ZNotes	**LINK**	
Canva	**LINK**	Designing of figures and diagrams
Geogebra	**LINK**	Vector diagrams
AS/A Level Syllabus	**LINK**	Checking syllabus

2023

Physical Quantities and Units

Physics