HL IB Physics

Measurements in Physics

Contents

Fundamental & Derived Units in IB Physics

SI Units & Prefixes

- There is a seemingly endless number of units in Physics
- These can all be reduced to seven base units from which every other unit can be derived
- These seven units are referred to as the SI Base Units; making up the system of measurement officially used in almost every country around the world

SI Base Quantities Table

Quantity	Si Base Unit	Symbol
Mass	Kilogram	kg
Length	Metre	m
Time	Second	s
Current	Ampere	A
Temperature	Kelvin	K
Amount of Substance	Mole	mol

Six SI quantities are shown. The seventh quantity, the candela, measures luminous intensity and is not covered in IB Physics. You may meet it later if you continue with Physics at university.

Derived Units

- Derived units are derived from the seven SI Base units
- The base units of physical quantities such as:
  - Newtons, **N**
  - Joules, **J**
  - Pascals, **Pa,** can be deduced

- To deduce the base units, it is necessary to use the definition of the quantity
- The Newton (N), the unit of force, is defined by the equation:
  - Force = mass × acceleration
  - $N = kg \times m\,s^{-2} = kg\,m\,s^{-2}$
  - Therefore, the Newton (N) in SI base units is $\mathbf{kg\,m\,s^{-2}}$

- The Joule (J), the unit of energy, is defined by the equation:
  - Energy = ½ × mass × velocity^2
  - $J = kg \times (m\,s^{-1})^2 = kg\,m^2\,s^{-2}$
  - Therefore, the Joule (J) in SI base units is $\mathbf{kg\,m^2\,s^{-2}}$

- The Pascal (Pa), the unit of pressure, is defined by the equation:
  - Pressure = force ÷ area
  - $Pa = N \div m^2 = (kg\,m\,s^{-2}) \div m^2 = kg\,m^{-1}\,s^{-2}$
  - Therefore, the Pascal (Pa) in SI base units is $\mathbf{kg\,m^{-1}\,s^{-2}}$

Using Scientific Notation in Physics

Orders of Magnitude

- When a number is expressed in an **order of 10**, this is an **order of magnitude**
  - For example, if a number is described as 3×10^8 then that number is actually 3 × 100 000 000
  - The **order of magnitude** of 3×10^8 is just $\mathbf{10^8}$
- When the number is greater than 5, round up to the next order of magnitude
  - For example, the **order of magnitude** of 6×10^8 is $\mathbf{10^9}$
- A quantity is an order of magnitude **larger** than another quantity if it is about **ten times larger**
- Similarly, **two orders of magnitude** would be **100 times larger,** or 10^2
  - In physics, orders of magnitude can be very large or very small
- When estimating values, it's best to give the **estimate** of an order of magnitude to **the nearest power of 10**
  - For example, the diameter of the Milky Way is approximately 1 000 000 000 000 000 000 000 m
- It is inconvenient to write this many zeros, so it's best to use **scientific notation** as follows:

$$1\,000\,000\,000\,000\,000\,000\,000 = 1 \times 10^{21} \text{ m}$$

- The order of magnitude is 10^{21}
- Orders of magnitude make it easier to compare the relative sizes of objects
  - For example, a quantity with an order of magnitude of 10^6 is 10 000 times larger than a quantity with a magnitude of 10^2

Approximation & Estimation

- To estimate is to obtain an approximate value
  - For **very** large or small quantities, using **orders of magnitudes** to estimate calculations is a valid approach
- Estimation is typically done to the nearest order of magnitude

Estimating Physical Quantities Table

Object of Interest	Approximate Length (m)	Order of Magnitude (m)
distance to the edge of the observable Universe	4.40×10^{26}	10^{26}
distance from Earth to Neptune	4.5×10^{12}	10^{12}
distance from London to Cape Town	9.7×10^{6}	10^{7}
length of a human	1.7	10^{0}

length of an ant	9×10^{-4}	10^{-3}
length of a bacteria cell	2×10^{-6}	10^{-6}

Worked example

Estimate the order of magnitude of the following:

(a) The temperature of an oven (in Kelvin)

(b) The volume of the Earth (in m^3)

(c) The number of seconds in a person's life if they live to be 95 years old

Answer:

(a) The temperature of an oven

Step 1: Identify the approximate temperature of an oven

- A conventional oven works at ~200 °C which is 473 K

Step 2: Identify the order of magnitude

- Since this could be written as 4.73×10^2 K
- The order of magnitude is $\sim 10^2$

(b) The volume of the Earth

Step 1: Identify the approximate radius of the Earth

- The radius of the Earth is $\sim 6.4 \times 10^6$ m

Step 2: Use the radius to calculate the volume

- The volume of a sphere is equal to:

$$V = 4/3\,\pi\, r^3$$

$$V = 4/3 \times \pi \times (6.4 \times 10^6)^3$$

$$V = 1.1 \times 10^{21}\ m^3$$

Step 3: Identify the order of magnitude

- The order of magnitude is $\sim 10^{21}$

(c) The number of seconds in 95 years

Step 1: Find the number of seconds in a single year

1 year = 365 days with 24 hours each with 60 minutes with 60 seconds

$$365 \times 24 \times 60 \times 60 = 31\,536\,000 \text{ seconds in a year}$$

Step 2: Find the number of seconds in 95 years

$$95 \times 31\,536\,000 = 283\,824\,000 \text{ seconds}$$

- This is approximately 2.84×10^8 seconds
- Therefore the order of magnitude is ~10^8

Scientific Notation

- In physics, **measured quantities** cover a large range from the very large to the very small
- Scientific notation is a form that is based on powers of 10
- The scientific form must have **one digit** in front of the decimal place
  - Any remaining digits remain behind the decimal place
  - The magnitude of the value comes from multiplying by 10^n where n is called 'the power'
  - This power is positive when representing large numbers or negative when representing small numbers

Worked example

Express 4 600 000 in scientific notation.

Answer:

Step 1: Write the convention for scientific notation

- To convert into scientific notation, only one digit may remain in front of the decimal point
  - Therefore, the scientific notation must be 4.6×10^n
- The value of *n* is determined by the number of decimal places that must be moved to return to the original number (i.e. 4 600 000)

Step 2: Identify the number of digits after the 4

- In this case, that number is +6

Step 3: Write the final answer in scientific notation

- The solution is: $\mathbf{4.6 \times 10^6}$

Metric Multipliers

- When dealing with magnitudes of 10, there are **metric names** for many common quantities
- These are known as metric multipliers and they change the **size** of the **quantity** they are applied to
  - They are represented by prefixes that go in front of the measurement
- Some common examples that are well-known include
  - **kilo**metres, **k**m ($\times 10^3$)
  - **centi**metres, **c**m ($\times 10^{-2}$)
  - **milli**grams, **m**g ($\times 10^{-3}$)

- Metric multipliers are represented by a single letter symbol such as centi- (c) or Giga- (G)
  - These letters go in front of the quantity of interest
  - For example, centimetres (cm) or Gigawatts (GW)

Common Metric Multipliers Table

Prefix	Abbreviation	Value
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
deca	da	10^{1}
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}

Worked example

What is 3.6 Mm + 2700 km, in m?

Answer:

Step 1: Check which metric multipliers are in this problem

- M represents **Mega–** which is **× 10^6** (not milli- which is small m!)
- k represents **kilo–** which is a multiplier of **× 10^3**

Step 2: Apply these multipliers to get both quantities to be metres

$$3.6 \times 10^6 \text{ m} + 2.7 \times 10^6 \text{ m}$$

Step 3: Write the final answer in units of metres

$$6.3 \times 10^6 \text{ m}$$

Significant Figures

- Significant figures are the digits that accurately represent a given quantity
- Significant figures describe the precision with which a quantity is known
  - If a quantity has **more significant figures** then **more precise** information is known about that quantity

Rules for Significant Figures

- Not all digits that a number may show are significant
- In order to know how many digits in a quantity are significant, these rules can be followed
  - **Rule 1:** In an integer, all digits count as significant if the last digit is non-zero
    - **Example:** 702 has 3 significant figures
  - **Rule 2:** Zeros at the end of an integer do not count as significant
    - **Example:** 705,000 has 3 significant figures
  - **Rule 3:** Zeros in front of an integer do not count as significant
    - **Example:** 0.002309 has 4 significant figures
  - **Rule 4:** Zeros at the end of a number less than zero count as significant, but those in front do not.
    - **Example:** 0.0020300 has 5 significant figures
  - **Rule 5:** Zeros after a decimal point are also significant figures.
    - **Example:** 70.0 has 3 significant figures
- Combinations of numbers must always be to the smallest number significant figures

Worked example

What is the solution to this problem to the correct number of significant figures: 18 × 384?

Answer:

Step 1: Identify the smallest number of significant figures

- 18 has only 2 significant figures, while 384 has 3 significant figures
- Therefore, the final answer should be to 2 significant figures

Step 2: Do the calculation with the maximum number of digits

$$18 \times 384 = 6912$$

Step 3: Round to the final answer to 2 significant figures

$$6.9 \times 10^3$$

Using Dimensional Analysis

Using Dimensional Analysis

- An important skill is to be able to check the homogeneity of physical equations using the SI base units
  - This is also known as **dimensional analysis**
- The units on either side of the equation should be the same
- To check the homogeneity of physical equations:
  - Check the units on both sides of an equation
  - Determine if they are equal
  - If they do not match, the equation will need to be adjusted

Measurement Techniques in IB Physics

Measurement Techniques

- Common instruments used in Physics are:
  - **Metre rules** - to measure distance and length
  - **Thermometers** - to measure temperature
  - **Measuring cylinders** - to measure to volume of liquid or the volume of displaced liquid
  - **Balances** - to measure mass
  - **Newtonmeters** - to measure force
  - **Protractors** - to measure angles
  - **Stopwatches** - to measure time
  - **Ammeters** - to measure current
  - **Voltmeters** - to measure potential difference
  - **Sound meter** - to measure the intensity of sound
  - **Light meter** - to measure the intensity of light
- More complicated instruments such as the **micrometer** screw gauge and **Vernier calipers** can be used to measure thicknesses, diameters and lengths to a greater degree of accuracy

- When using measuring instruments like these you need to ensure that you are fully aware of what each division on a scale represents
  - This is known as the **resolution**
- The resolution is the smallest change in the physical quantity being measured that results in a change in the reading given by the measuring instrument
- The smaller the change that can be measured by the instrument, the greater the degree of resolution
- For example, a standard mercury thermometer has a resolution of 1°C whereas a typical digital thermometer will have a resolution of 0.1°C
  - The digital thermometer has a higher resolution than the mercury thermometer

Measuring Instruments Table

Quantity	Instrument	Typical Resolution
Length	Meter Rule	1 mm
Thickness or length	Vernier Calipers	0.05 mm
Thickness or length	Micrometer	0.001 mm
Mass	Top-Pan Balance	0.01 g
Angle	Protractor	1°
Time	Stopwatch	0.01 s
Temperature	Thermometer	1 °C
Potential Difference	Voltmeter	1 mV - 0.1 V
Current	Ammeter	1 mA - 0.1 A

Controlling Variables

- For an experiment to be **valid**, it is essential that any variable that may affect the outcome of an experiment is controlled
- Some of the key practical skills that are required to do so are as follows:
  - Calibration of measuring apparatus
  - Keeping certain environmental conditions constant
  - Insulation against heat loss or gain
  - Reduction of friction
  - Reduction of electrical resistance
  - Taking background radiation into account

Calibration of Measuring Apparatus

- Calibration is a comparison between a **known** measurement and the measurement you achieve using the instrument
- This checks the accuracy of the instrument, especially for higher readings
  - For example, checking whether a meter (e.g., voltmeter, micrometer, ammeter) reads **zero** before measurements are made
  - This helps to avoid zero error

Calibrating sensors

- Calibration curves are used to **convert measurements** made on one measurement scale to another measurement scale
- These are useful in experiments when the instruments used have outputs which are not proportional to the value they are measuring
  - For example, e.m.f and temperature (thermocouple) or resistance against temperature (thermistor)

- The calibration curve for a thermocouple, in which the e.m.f varies with temperature, is shown below:

Maintaining Constant Conditions

- In an experiment, a variable is any factor that could change or be changed
- There are different types of variables within an experiment
  - The **independent variable**: the only variable that should be changed throughout an experiment
  - The **dependent variable**: the variable that is measured to determine the outcome of an experiment (the results)
  - The **controlled variables**: any other variables that may affect the results of the experiment that need to be controlled or monitored

- It is essential that any variable that may affect the outcome of an experiment is controlled in order for the results to be **valid** and to have a **fair test**
  - A fair test is one in which **only** the independent variable has been allowed to affect the dependent variable

Controlling Heat Losses & Gains

- Energy transfers by heating due to **conduction** are one of the most common sources of dissipated energy
- To reduce energy transfers by **conduction**, materials with a **low** thermal conductivity should be used
  - Materials with low thermal conduction are called **insulators**
- **Insulation** reduces energy transfers from both **conduction** and **convection**
- The effectiveness of an insulator is dependent upon:

  1. The thermal conductivity of the material
  - The lower the conductivity, the lower the amount of heat loss

  2. The density of the material
  - The more dense the insulator, the more conduction can occur
  - In a denser material, the particles are closer together so they can transfer energy to one another more easily

  3. The thickness of the material
  - The thicker the material, the lower the amount of heat loss

Reducing Friction

- In a mechanical system, there is often **friction** between the moving parts of the machinery
- This results in unwanted energy transfers **by heating** the machinery and the surroundings
- **Friction** can be reduced by:
  - Adding bearings to prevent components from directly rubbing together
  - Lubricating parts

Reducing Electrical Resistance

- In electric circuits, there is **resistance** as current flows through the wires and components
- This results in unwanted energy transfers **by heating** to the wires, components and the surroundings
- **Resistance** can be reduced by:
  - Using components with lower resistance
  - Reducing the current

Adjusting for Background Radiation

- Although most background radiation is natural, a small amount of it comes from artificial sources, such as **medical procedures** (including X-rays)
- Levels of background radiation can vary significantly from place to place
- When conducting experiments to measure the radiation coming from radioactive sources, the background radiation must be taken into account, to do this:
  - Place a **Geiger-Muller tube** away from any radioactive sources and measure the **background count**
  - Carry out the experiment with the radioactive source
  - Subtract the background count from each reading to obtain the count rate from the source only