1 Physical Quantities, Units and Measurement

Study Station ▸▸

A Physical Quantities and Units

Learning Outcomes

- Understand that physical quantities typically consist of a numerical magnitude and a unit.
- Recall the six common base quantities and their units: mass (kg), length (m), time (s), current (A), temperature (K), amount of substance (mol).
- Use the common prefixes and their symbols to indicate decimal sub-multiples and multiples of the SI units: nano (n), micro (μ), milli (m), centi (c), deci (d), kilo (k), mega (M), giga (G), tera (T).

1. **Physics** is the *scientific discipline or group of knowledge that helps us to understand the physical world around us*. We also use knowledge of physics to create many useful technologies in our daily lives such as the smartphone, computer and television, which are important in modern society.

2. All objects in our physical world can be described by their physical quantities. A **physical quantity** is a *quantity that can be measured*. It typically consists of a numerical magnitude (number) and a unit.

Example: Length of a book = 0.16 metre

- Length → physical quantity
- book → object
- 0.16 → magnitude
- metre → unit

3. The **SI units** are an internationally agreed standard of units used worldwide.
   - The **six base SI units** correspond to the **six common base quantities**.

Base Quantity and Common Symbol	SI Base Unit and Symbol
length, l	metre, m
time, t	second, s
mass, m	kilogram, kg
temperature, T	kelvin, K
amount of substance, n	mole, mol
electric current, I	ampere, A

- All other physical quantities can be derived from the base quantities. They are called **derived quantities** with units known as **derived units.**

Example of Derived Quantity	Derivation of Unit	Derived Unit
area = length × width	unit of area = unit of length × unit of width	m × m = m^2 (square metre or metres squared)
volume = length × width × height	unit of volume = unit of length × unit of width × unit of height	m × m × m = m^3 (cubic metre or metres cubed)
speed = $\frac{\text{distance}}{\text{time}}$	unit of speed = $\frac{\text{unit of distance}}{\text{unit of time}}$	m/s (metre per second)

Common Error

✗ speed v = 20 m/s^{-1}

✓ speed v = 20 m s^{-1} = 20 m/s

✗ density ρ = 19 g/cm^{-3}

✓ density ρ = 19 g cm^{-3} = 19 g/cm^3

4. For physical quantities with very big or very small magnitudes, we can write them in the **standard form** in the format: $A \times 10^n$ with $1 \leq A < 10$, where n is an integer.

Example of Physical Quantity	Magnitude and Unit	Standard Form
Length of Formula 1 Singapore Grand Prix circuit	30 900 m	3.09×10^5 m
Speed of light in vacuum	300 000 000 m/s	3.0×10^8 m/s
Diameter of a hydrogen atom	0.000 000 000 05	5×10^{-11} m

5. We can also use common **prefixes** to represent sub-multiples and multiples of 10 of the SI units.

Common Prefix and Symbol	Conversion Using Example of Metre
nano, n	1 nm = 1×10^{-9} m
micro, μ (pronounced 'mu', Greek letter 'm')	1 μm = 1×10^{-6} m
milli, m	1 mm = 1×10^{-3} m
centi, c	1 cm = 1×10^{-2} m
deci, d	1 dm = 1×10^{-1} m
kilo, k	1 km = 1×10^{3} m
mega, M	1 Mm = 1×10^{6} m
giga, G	1 Gm = 1×10^{9} m
tera, T	1 Tm = 1×10^{12} m

Tip

The six SI units are metre, second, kilogram, kelvin, mole and ampere. Note that kilogram is the only SI base unit which has a prefix.

Common Error

✗ 1 m = 100 cm
Therefore 1 m^2 = 100 cm^2

✓ 1 m = 100 cm
Therefore 1 m^2 = 1 m × 1 m = 100 cm × 100 cm = 10 000 cm^2

Worked Example 1.1

Which one is bigger, a dust particle of size 150 µm or the air filter hole of size 0.0015 cm?

Strategy

Convert the two different units to a common unit before making a comparison.

Solution

Size of dust particle:

$$\begin{aligned} 150\ \mu m &= 150 \times 10^{-6}\ m \\ &= 1.5 \times 10^{2} \times 10^{-6}\ m \\ &= 1.5 \times 10^{-4}\ m \end{aligned}$$

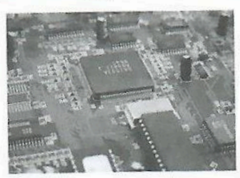
Size of air filter hole:

$$\begin{aligned} 0.0015\ cm &= 1.5 \times 10^{-3}\ cm \\ &= 1.5 \times 10^{-3} \times 10^{-2}\ m \\ &= 1.5 \times 10^{-5}\ m \end{aligned}$$

Therefore, the dust particle is bigger than the air filter hole.

Worked Example 1.2

According to the Singapore government agency EDB, the electronics industry manufactured products worth USD 64.8 billion in 2015, amounting to 31.6% of total manufacturing output. This important industry produces many highly advanced products including the microchip which is the 'brain' of many modern electronic devices, such as smartphones and computers.



(a) The features in a microchip are about 10 nm in size. In comparison, a human hair diameter is about 0.1 mm. How much larger is the human hair compared to the microchip features?

(b) Why is microchip manufacturing considered a highly advanced industry?

Strategy

Convert the two different units to a common unit before making a comparison.

Solution

(a) Size of microchip features

$$\begin{aligned} &= 10\ nm = 10 \times 10^{-9}\ m \\ &= 10 \times 10^{-6} \times 10^{-3}\ m \\ &= 10 \times 10^{-6}\ mm \\ &= 1 \times 10^{-5}\ mm \end{aligned}$$

Ratio of human hair diameter to the size of microchip features $= \dfrac{0.1\ mm}{10 \times 10^{-6}\ mm} = 10\ 000$

Therefore, the human hair is 10 000 times the size of the microchip features.

(b) Highly advanced machines are needed to manufacture very small products such as the microchip.

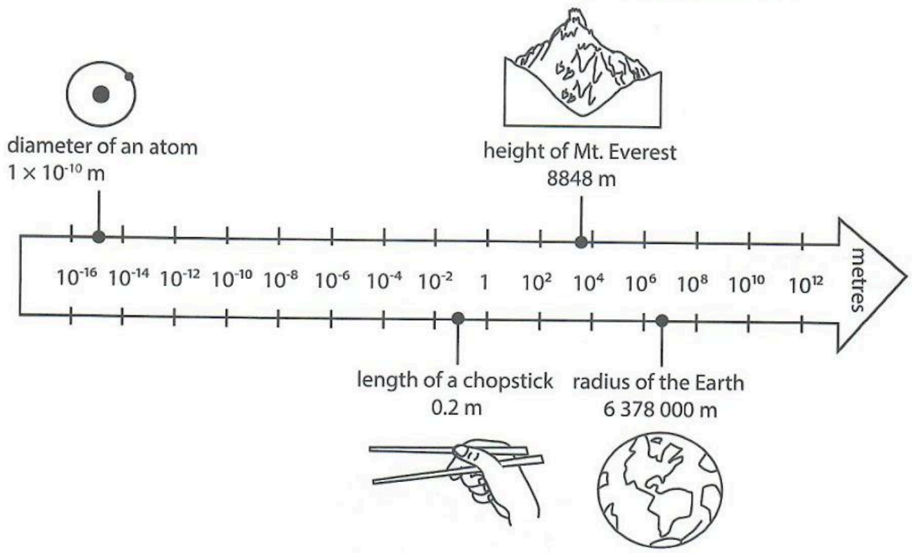
Link — Discover Physics (5th Edition) Textbook — Section 1.2

B Measurement of Physical Quantities

Learning Outcomes

- Understand the orders of magnitude of common objects with sizes ranging from a typical atom to the Earth.
- Select suitable measuring instruments and explain how to use them to measure common physical quantities taking into consideration the range and precision of the instrument.

1. We can sort out the objects in our physical world from very small to very large using their **orders of magnitude**.
   - Size of a typical atom = 1×10^{-10} m (standard form). Its order of magnitude is –10.
   - Size of the Earth = 6.378×10^{6} m (standard form). Its order of magnitude is 6.



2. We can measure the *physical quantity of length* using various **measuring instruments**.
   - The **measuring tape** is commonly used to measure objects that are longer than a metre.

   - The **metre rule** is commonly used to measure objects that are several centimetres to one metre.

- The **digital calipers** are a useful instrument to measure an object's internal and external diameters and depths that are between 1 cm and 15 cm.

- The digital **micrometer screw gauge** is used to measure objects that are very small.

3. We choose the most suitable measuring instrument based on its precision and range.
   - **Precision** is the smallest value that an instrument can measure.
   - **Range** is the bracket of values that an instrument can measure.

Instrument	Precision	Range	Example of Usage
Measuring tape	0.1 cm or 1 mm	Up to several metres	Length of a room
Metre rule	0.1 cm or 1 mm	Up to one metre	Length of a book
Digital calipers	0.001 cm or 0.01 mm	Between 1 cm and 15 cm	Diameter of a test tube
Digital micrometer screw gauge	0.0001 cm or 0.001 mm	Less than 2.5 cm	Diameter of a wire

Worked Example 1.3

The user guide of a digital micrometer screw gauge states that its precision is 0.0001 cm and its range is 2.5 cm. A student used the digital micrometer screw gauge to measure the dimensions of a piece of wire.

(a) The student recorded that the diameter of the wire is 1.526 42 cm. Explain why this is wrong.

(b) The student recorded that the length of the wire is 5.6283 cm. Explain why this is also wrong.

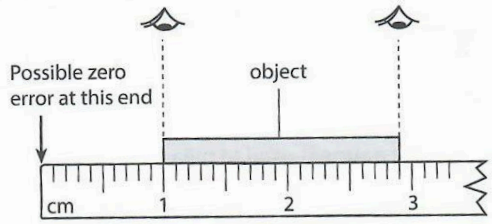
Solution

(a) The precision of the micrometre screw gauge is 0.0001 cm which means the measured value cannot be more precise than this. Possible measured values are 1.5264 cm or 1.5265 cm.

(b) The range of the micrometre screw gauge is 2.5 cm, which is the largest length that can be measured. Thus, it cannot be used to accurately measure objects larger than 2.5 cm.

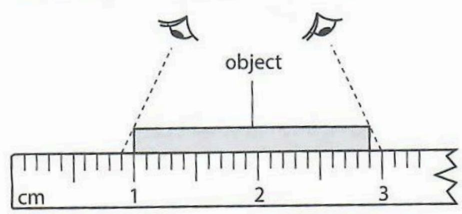
4. Errors can occur during measurement.
   - **Parallax errors** are caused by the *inaccurate positioning of the observer's eye* while taking readings. To avoid parallax errors, the eye should be positioned directly above the markings.

Accurate length of object = 2.9 cm – 1.0 cm = 1.9 cm



Correct positioning of the eye

Inaccurate length of object = 3.0 cm – 0.9 cm = 2.1 cm



Incorrect positioning of the eye

   - **Zero error** is the *non-zero reading when we expect a zero reading*. For example, an end of a metre rule starts at 0.1 cm instead of 0 cm due to the wear and tear at the zero end of the ruler. An accurate reading can be obtained by subtracting the zero error from the measured reading.

Corrected reading = measured reading – zero error

Worked Example 1.4

A pair of digital calipers gives readings of –0.2 mm when it is closed and 3.5 mm when it is measuring the width of an object.

(a) State the zero error.

(b) Calculate the corrected reading for the width of the object.

Strategy

(a) Recall that zero error occurs when the measuring instrument is supposed to give a reading of 0 mm.

Solution

(a) –0.2 mm

(b) Corrected reading = measured reading – zero error
= 3.5 mm – (–0.2 mm)
= 3.7 mm

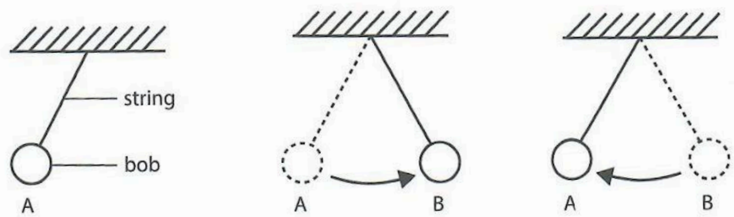
Explanation

Note that the value of zero error can also be negative.

5. We can measure the *physical quantity of time* using a **stopwatch**.

Digital stopwatch

6. The **simple pendulum** consists of a heavy object, called a *bob, attached to a string*. The bob swings back and forth, or **oscillates**. The time taken for the pendulum to complete a full oscillation is called its **period**.



7. We can use the stopwatch to **measure the period** T of the simple pendulum.
   (a) Allow the bob to swing back and forth in a small angle. Start the stopwatch when the pendulum is at the highest point and it is momentarily stationary to reduce random error.
   (b) Count the number of full oscillations. Stop the stopwatch when 20 full oscillations are complete.
   (c) Divide the time taken by the number of oscillations to obtain the *average time taken for each oscillation*, or the period.

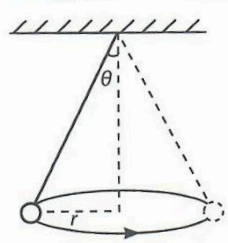
$$\text{Period } T = \frac{t_{20}}{20}$$

Tip

The period T of a simple pendulum does not depend on the mass of the bob or the angle of swing (as long as the angle of swing is small). The period T depends on the length of the string with g as a constant.

$$\text{Period } T = 2\pi\sqrt{\frac{l}{g}}$$

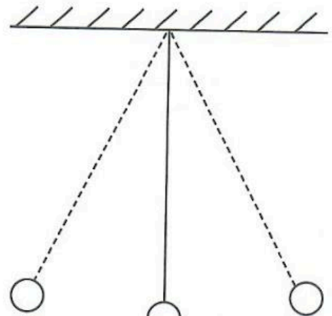
8. A common error occurs when the bob of the pendulum moves in a circular path rather than back and forth. This is called a conical pendulum which has a different period from a simple pendulum.



A conical pendulum traces the shape of a cone with an angle θ and a radius r.

Worked Example 1.5

The bob of the pendulum shown was pulled to position **P** and then released. The time taken for the pendulum to swing 20 oscillations is 10 s.



(a) What is the period of the pendulum?

(b) What is the time taken for the pendulum to swing from **P** to **Q**?

Solution

(a) Period of pendulum $= \frac{t_{20}}{20}$

$= \frac{10\text{ s}}{20}$

$= 0.50\text{ s}$

(b) Time taken to swing from **P** to **Q** $= \frac{0.50\text{ s}}{2} = 0.25\text{ s}$

Explanation

The bob completes half an oscillation when it swings from **P** to **Q**.

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Checkpoint 1.1

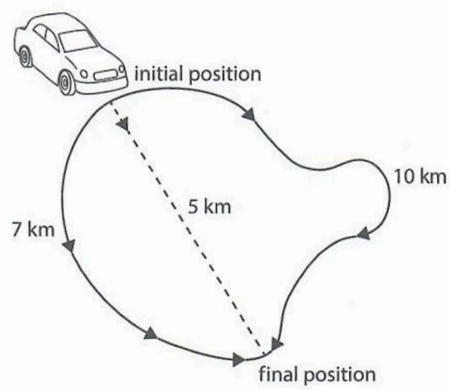
1. A student decides to use the digital micrometer screw gauge to measure everything because it has the best precision. Explain why this decision may not be wise.

C Scalar and Vector Quantities

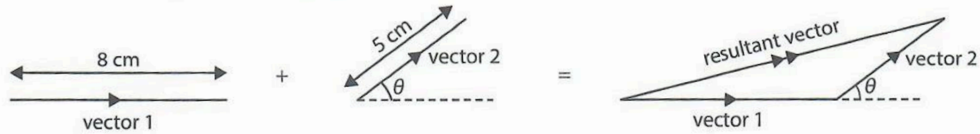
Learning Outcomes

- State the meaning of scalar and vector quantities and give common examples of each.
- Add two vectors to determine a resultant vector using the graphical method.

1. Physical quantities can be categorised into either scalar or vector quantities.
   - A **scalar quantity** has *magnitude but not direction.*
   - A **vector quantity** has *both magnitude and direction.*
2. A car has a choice of two routes of lengths 7 km or 10 km to reach a destination located 5 km away.



   - The **distance travelled** is a scalar quantity. The distance travelled by the car is either 7 km or 10 km depending on the route taken.
   - The **displacement** is a *measure of the shortest distance from the initial position to the final position.* Thus, the displacement of the car is 5 km in the direction shown by the dotted arrow. Note that the displacement is the same no matter which route the car takes.
3. Adding or subtracting scalar quantities is not unlike adding or subtracting numbers. For example, total time taken = 15 s + 10 s = 25 s.
4. Adding or subtracting vector quantities requires a different method. For example, we can use the **tip-to-tail graphical method** to add two vectors.
   (a) Determine the arrow length which must be proportional to the vector magnitude.
   (b) Draw a vector diagram with the tip of one vector coinciding with the tail of the other vector. The arrows must point in the direction of the vectors they represent.
   (c) Draw the resultant vector as shown below.



Tip-to-tail method

Worked Example 1.6

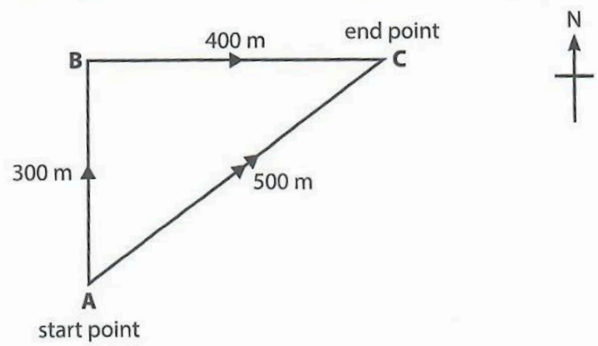
A man goes hiking in the forest and walks 300 m towards the north before walking a further 400 m towards the east. How far is he now from the starting point?

Strategy

Initial displacement is 300 m towards the north. Second displacement is 400 m towards the east. The total displacement can be found by adding the two displacements using a graphical method.

Solution

Using a scale of 1 cm : 100 m, the path of the man can be represented by the diagram below.



(a) Measured from the diagram, **AC** = 5 cm.

As 1 cm represents 100 m, 5 cm represents 500 m.

Therefore, the man is 500 m away from the starting point.

Explanation
AB is vertical while **BC** is horizontal, so **ABC** is a right-angled triangle. Thus, it is also possible to solve this question mathematically using Pythagoras' Theorem.

Using Pythagoras' Theorem, calculate using only the magnitudes,

$$\mathbf{AC}^2 = 300^2 + 400^2$$

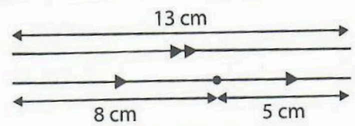
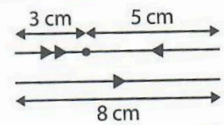
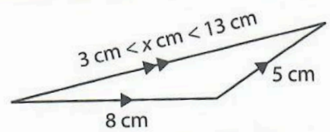
$$\mathbf{AC}^2 = 250\,000$$

$$\mathbf{AC} = 500$$

Therefore, **AC** is 500 m.

If the question specifically states to use the graphical method, you must draw a scaled vector diagram. The mathematical method may be used afterwards to check the answer obtained.

5. When adding two vectors, the angle between the vectors determine the magnitude of the resultant vector.

The magnitude of the resultant vector is maximum when both vectors are in the same direction.	
The magnitude of the resultant vector is minimum when both vectors are in the opposite directions.	
The magnitude of the resultant vector is between the minimum and maximum when the two vectors are in any other directions.	

Tip

When solving a question on vector quantities, you should draw a vector diagram to help you understand the question correctly even if the question does not specifically require the vector diagram.

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Checkpoint 1.2

1. A ship sailed 3 km in a certain direction. It then changed direction and sailed another 5 km. Which of the following **cannot** be the distance from its starting point to its current position?

   A 1 km

   B 2 km

   C 8 km

   D 5.83 km

Test Station

1. A water pipe of has an approximate length of 80 cm and an approximate internal diameter of 2 cm. Which instruments are the most suitable to measure the length and internal diameter of the pipe accurately?

   A Length: Measuring tape
   Internal diameter: Metre rule

   B Length: Metre rule
   Internal diameter: Digital micrometer screw gauge

   C Length: Metre rule
   Internal diameter: Digital calipers

   D Length: Digital calipers
   Internal diameter: Digital micrometer screw gauge

2. Which of the following actions can be taken to reduce parallax errors?

   A Use a newer measuring instrument.

   B Take readings in a brighter place.

   C Use a more precise measuring instrument.

   D Position the eye directly above the marking.

3. Prefixes are commonly used in many fields in the real world. Answer the following questions and express your answers in standard form.

   (a) Virologists study viruses including the SARS-CoV-2 virus, which caused the COVID-19 global pandemic in 2019 (Figure 1.1). This virus is about 100 nm in diameter.

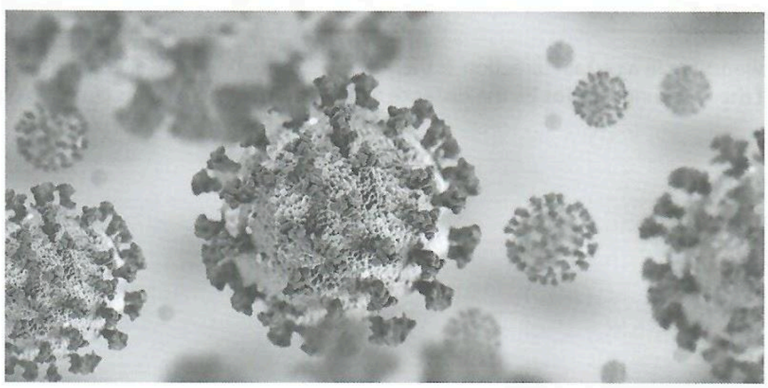

Figure 1.1

   State the diameter of this virus in metres. [1]

   (b) Health ministries around the world often publish dietary recommendations as public health advice. The Ministry of Health in Singapore recommends a daily intake of 2.2 μg of vitamin B12 for a healthy 15-year-old girl.

   State the recommended daily intake in grams. [1]

   (c) The camera quality of modern smartphones are indicated by their number of pixels. A certain smartphone has a 108 megapixel camera.

   Express 108 megapixels in pixels. [1]

4. A jogger uses an app on his smartphone to record his running distance. The app also tracks his location on a map.

   (a) The jogger runs from town **A** to town **B**. The app indicates that he has run 10 km.

   However, the displacement between town **A** and town **B** shown on the map is 9.5 km.

   Give a possible reason for the discrepancy in the two values. [1]

   (b) The jogger runs for another 5 km from town **B** to town **C**. What is the total distance run by the jogger as he runs from town **A** to town **C**? [2]

5. A student has to determine how the period *T* of a simple pendulum varies with its length *l* for small displacements of the pendulum bob. He measures the pendulum length using a metre rule and measures the time taken by the pendulum for 20 oscillations using a digital stopwatch.

   (a) The student obtained the following raw data. Complete the table below with suitable headings and fill in the corresponding values that will be useful for recording the results obtained. The length *l* and the period *T* should also be shown in the table. [9]

	Time for 20 Oscillations			
100.0	40.37	40.14		
90.0	38.08	38.12		
80.0	35.89	35.80		
70.0	33.48	33.58		
60.0	30.97	30.93		
50.0	28.17	28.14		

   (b) How does the period *T* vary with the length *l* of the pendulum? [2]