Physics

Physics, the most fundamental physical science, is concerned with the fundamental principles of the Universe.

It is the foundation upon which the other sciences—astronomy, biology, chemistry, and geology—are based.

It is also the basis of a large number of engineering applications.

The beauty of physics lies in the simplicity of its fundamental principles and in the manner in which just a small number of concepts and models can alter and expand our view of the world around us.

The study of physics can be divided into six main areas:

1. ***classical mechanics,*** concerning the motion of objects that are large relative to atoms and move at speeds much slower than the speed of light
2. ***relativity,*** a theory describing objects moving at any speed, even speeds approaching the speed of light
3. ***thermodynamics,*** dealing with heat, work, temperature, and the statistical behavior of systems with large numbers of particles
4. ***electromagnetism***, concerning electricity, magnetism, and electromagnetic fields
5. ***optics,*** the study of the behavior of light and its interaction with materials
6. ***quantum mechanics***, a collection of theories connecting the behavior of matter at the submicroscopic level to macroscopic observations

Objective of Physics

- To find the limited number of fundamental laws that govern natural phenomena
- To use these laws to develop theories that can predict the results of future experiments
- Express the laws in the language of mathematics

1. Physics and Measurement

1.1 Standards of Length, Mass, and Time

Measurements

- Used to describe natural phenomena
- Each measurement is associated with a physical quantity
- Need defined standards
- Characteristics of standards for measurements
  - Readily accessible
  - Possess some property that can be measured reliably
  - Must yield the same results when used by anyone anywhere
  - Cannot change with time

Quantities used in Mechanics

In mechanics, three fundamental quantities are used:

Length

Length is the distance between two points in space.

Defined in terms of a meter (m) in SI-Unit.

The meter is defined as the distance traveled by light in vacuum during a time of 1/299 792 458 second.

Table 1.1 **Approximate Values of Some Measured Lengths**

	Length (m)
Distance from the Earth to the most remote known quasar	1.4×10^{26}
Distance from the Earth to the most remote normal galaxies	9×10^{25}
Distance from the Earth to the nearest large galaxy (Andromeda)	2×10^{22}
Distance from the Sun to the nearest star (Proxima Centauri)	4×10^{16}
One light-year	9.46×10^{15}
Mean orbit radius of the Earth about the Sun	1.50×10^{11}
Mean distance from the Earth to the Moon	3.84×10^{8}
Distance from the equator to the North Pole	1.00×10^{7}
Mean radius of the Earth	6.37×10^{6}
Typical altitude (above the surface) of a satellite orbiting the Earth	2×10^{5}
Length of a football field	9.1×10^{1}
Length of a housefly	5×10^{-3}
Size of smallest dust particles	$\sim 10^{-4}$
Size of cells of most living organisms	$\sim 10^{-5}$
Diameter of a hydrogen atom	$\sim 10^{-10}$
Diameter of an atomic nucleus	$\sim 10^{-14}$
Diameter of a proton	$\sim 10^{-15}$

Mass

Defined in terms of a kilogram (kg).

The kilogram (kg), is defined as the mass of a specific platinum–iridium alloy cylinder kept at the International Bureau of Weights and Measures at Sèvres, France.

Table 1.2

Approximate Masses of Various Objects

	Mass (kg)
Observable Universe	$\sim 10^{52}$
Milky Way galaxy	$\sim 10^{42}$
Sun	1.99×10^{30}
Earth	5.98×10^{24}
Moon	7.36×10^{22}
Shark	$\sim 10^{3}$
Human	$\sim 10^{2}$
Frog	$\sim 10^{-1}$
Mosquito	$\sim 10^{-5}$
Bacterium	$\sim 1 \times 10^{-15}$
Hydrogen atom	1.67×10^{-27}
Electron	9.11×10^{-31}

Time

Defined in terms of the oscillation of radiation from a cesium atom.

Defined in terms of seconds (s).

In 1967, the second was redefined to take advantage of the high precision attainable in a device known as an atomic clock, which measures vibrations of cesium atoms.

One second is now defined as 9 192 631 770 times the period of vibration of radiation from the cesium-133 atom.

Fundamental and Derived Quantities

Fundamental quantities: the variables length, mass, and time.

Derived quantities: those variables that can be expressed as a mathematical combination of the three fundamental quantities.

- Common examples are:

  area (a product of two lengths)

  speed (a ratio of a length to a time interval).

Prefixes

In addition to the fundamental SI units of meter, kilogram, and second, we can also use other units, such as millimeters and nanoseconds, where the prefixes *milli*- and *nano*- denote multipliers of the basic units based on various powers of ten.

Examples:

0.001 m= 10^{-3} m= 1mm

1000 g = 10^{+3}g = 1kg

Table 1.4 **Prefixes for Powers of Ten**

Power	Prefix	Abbreviation	Power	Prefix	Abbreviation
10^{-24}	yocto	y	10^{3}	kilo	k
10^{-21}	zepto	z	10^{6}	mega	M
10^{-18}	atto	a	10^{9}	giga	G
10^{-15}	femto	f	10^{12}	tera	T
10^{-12}	pico	p	10^{15}	peta	P
10^{-9}	nano	n	10^{18}	exa	E
10^{-6}	micro	μ	10^{21}	zetta	Z
10^{-3}	milli	m	10^{24}	yotta	Y
10^{-2}	centi	c			
10^{-1}	deci	d			

1.4 Dimensional Analysis

Dimension denotes the physical nature of a quantity.

The symbols used to specify the dimensions of length, mass, and time are L, M, and T, respectively.
Dimensions are often denoted with square brackets [ ]:
Length [L]
Mass [M]
Time [T]

Examples:
The dimensions of speed are written $[v] = L/T$
The dimensions of area A are $[A] = L^2$

Table 1.5 Dimensions and Units of Four Derived Quantities

Quantity	Area (A)	Volume (V)	Speed (v)	Acceleration (a)
Dimensions	L^2	L^3	L/T	L/T^2
SI units	m^2	m^3	m/s	m/s^2
U.S. customary units	ft^2	ft^3	ft/s	ft/s^2

Analysis of an Equation

You can use dimensional analysis to determine whether an expression has the correct form.

Any relationship can be correct only if the dimensions on both sides of the equation are the same.

Some Rules:

- Dimensions can be treated as algebraic quantities, quantities can be added or subtracted only if they have the same dimensions
- The terms on both sides of an equation must have the same dimensions

Example

Perform a dimensional check for the equation

$x = \frac{1}{2}\, a\, t^2$, where x represents position, a acceleration, and t an instant of time.

$$\mathrm{L} = \frac{\mathrm{L}}{\cancel{\mathrm{T}^2}} \cdot \cancel{\mathrm{T}^2} = \mathrm{L}$$

Example 1.2 Analysis of an Equation

Show that the expression $v = a\,t$, where v represents speed, a acceleration, and t an instant of time, is dimensionally correct.

SOLUTION

Identify the dimensions of v from Table 1.5: $$[v] = \frac{L}{T}$$

Identify the dimensions of a from Table 1.5 and multiply by the dimensions of t: $$[at] = \frac{L}{T^{\cancel{2}}}\cancel{T} = \frac{L}{T}$$

Therefore, $v = at$ is dimensionally correct because we have the same dimensions on both sides.

Analysis of a Power Law

A more general procedure using dimensional analysis is to set up an expression of the form

$$x \propto a^n t^m$$

- This relationship is correct only if the dimensions of both sides are the same.

Example Find the correct exponents *m* and *n* of the expression

$$x \propto a^n t^m$$

Because the dimension of the left side is length $[x] = \mathrm{L}$, the dimension of the right side must also be length L. That is,

$$[a^n t^m] = \mathrm{L}^1\mathrm{T}^0$$

$$(\mathrm{L}/\mathrm{T}^2)^n (T)^m = \mathrm{L}^1\mathrm{T}^0$$

$$\mathrm{L}^{\mathrm{n}}\,\mathrm{T}^{m-2n} = \mathrm{L}^1\mathrm{T}^0$$

$n = 1$

$m - 2n = 0 \rightarrow m = 2$

Returning to our original expression $x \propto a^n t^m$, we conclude that $x \propto a^1 t^2$.

Example 1.3 Analysis of a Power Law

Suppose we are told that the acceleration a of a particle moving with uniform speed v in a circle of radius r is proportional to some power of r, say r^n, and some power of v, say v^m. Determine the values of n and m and write the simplest form of an equation for the acceleration.

SOLUTION

Write an expression for a with a dimensionless constant of proportionality k:

$$a = kr^n v^m$$

Substitute the dimensions of a, r, and v:

$$\frac{\text{L}}{\text{T}^2} = \text{L}^n\left(\frac{\text{L}}{\text{T}}\right)^m = \frac{\text{L}^{n+m}}{\text{T}^m}$$

Equate the exponents of L and T so that the dimensional equation is balanced:

$$n + m = 1 \text{ and } m = \boxed{2}$$

Solve the two equations for n:

$$n = \boxed{-1}$$

Write the acceleration expression:

$$a = kr^{-1}v^2 = \boxed{k\frac{v^2}{r}}$$

In Section 4.4 on uniform circular motion, we show that $k = 1$ if a consistent set of units is used. The constant k would not equal 1 if, for example, v were in km/h and you wanted a in m/s^2.

1.5 Conversion of Units

Conversion factors between SI and U.S. customary units of length are as follows:

1 mile = 1 609 m = 1.609 km,

1 ft = 0.304 8 m = 30.48 cm

1 m = 39.37 in. = 3.281 ft,

1 in. = 0.025 4 m = 2.54 cm

Like dimensions, units can be treated as algebraic quantities that can cancel each other. For example, suppose we wish to convert 15.0 in. to centimeters. Because 1 in. is defined as exactly 2.54 cm, we find that

$$15.0 \text{ in.} = (15.0 \cancel{\text{in.}})\left(\frac{2.54 \text{ cm}}{1 \cancel{\text{in.}}}\right) = 38.1 \text{ cm}$$

Example 1.3 Is He Speeding?

On an interstate highway in a rural region of Wyoming, a car is traveling at a speed of 38.0 m/s. Is the driver exceeding the speed limit of 75.0 mi/h?

SOLUTION

Convert meters in the speed to miles:

Convert seconds to hours:

Example 1.4 Is He Speeding?

On an interstate highway in a rural region of Wyoming, a car is traveling at a speed of 38.0 m/s. Is the driver exceeding the speed limit of 75.0 mi/h?

SOLUTION

Convert meters in the speed to miles:

$$(38.0\ \cancel{\text{m}}/\text{s})\left(\frac{1\ \text{mi}}{1\ 609\ \cancel{\text{m}}}\right) = 2.36 \times 10^{-2}\ \text{mi/s}$$

Convert seconds to hours:

$$(2.36 \times 10^{-2}\ \text{mi}/\cancel{\text{s}})\left(\frac{60\ \cancel{\text{s}}}{1\ \cancel{\text{min}}}\right)\left(\frac{60\ \cancel{\text{min}}}{1\ \text{h}}\right) = 85.0\ \text{mi/h}$$

What is the speed of the car (85.0 mi/h) in km/h?

$$(85.0\ \cancel{\text{mi}}/\text{h})\left(\frac{1.609\ \text{km}}{1\ \cancel{\text{mi}}}\right) = 137\ \text{km/h}$$

1.6 Estimates and Order-of-Magnitude Calculations

1. Express the number in scientific notation, with the multiplier of the power of ten between 1 and 10 and a unit.
2. If the multiplier is less than 3.162 (the square root of 10), the order of magnitude of the number is the power of 10 in the scientific notation. If the multiplier is greater than 3.162, the order of magnitude is one larger than the power of 10 in the scientific notation.

We use the symbol $\sim$ for "is on the order of." Use the procedure above to verify the orders of magnitude for the following lengths:

$$0.008\,6 \text{ m} \sim 10^{-2} \text{ m} \qquad 0.002\,1 \text{ m} \sim 10^{-3} \text{ m} \qquad 720 \text{ m} \sim 10^{3} \text{ m}$$

Usually, when an order-of-magnitude estimate is made, the results are reliable to within about a factor of 10. If a quantity increases in value by three orders of magnitude, its value increases by a factor of about $10^3 = 1\,000$.

1.7 Significant Figures

When you compute a result from several measured numbers, each of which has a certain accuracy, you should give the result with the correct number of **significant figures.**

Significant Digit Rules:

1-All non-zero digits are significant

2-Leading zeros are not significant

3-Trailing zeros are significant where there is a decimal point in the number

4-Trailing zeros are not significant in numbers without decimal points.

5-In-between zeros are significant

Examples:

- 0.0075 m has 2 significant figures
  - The leading zeros are placeholders only
  - Can write in scientific notation to show more clearly: 7.5×10^{-3} m for 2 significant figures
- 10.0 m has 3 significant figures
  - The decimal point gives information about the reliability of the measurement
- 1500 m is ambiguous
  - Use 1.5×10^3 m for 2 significant figures
  - Use 1.50×10^3 m for 3 significant figures
  - Use 1.500×10^3 m for 4 significant figures

Operations with Significant Figures

When **multiplying or dividing** several quantities, the number of significant figures in the final answer is the same as the number of significant figures in the quantity having the smallest number of significant figures.

- ❑ Example: 25.57 m x 2.45 m = 62.6 m^2
  The 2.45 m limits your result to 3 significant figures

When numbers are **added** or **subtracted,** the number of decimal places in the result should equal the smallest number of decimal places of any term in the sum or difference.

- ❑ Example: 135 cm + 3.25 cm = 138 cm
  The 135 cm limits your answer to the units decimal value

Rounding off numbers

- Last retained digit is increased by 1 if the last digit dropped is greater than 5.
- Last retained digit remains as it is if the last digit dropped is less than 5.
- If the last digit dropped is equal to 5, the retained digit should be rounded to the nearest even number.
- Saving rounding until the final result will help eliminate accumulation of errors

Suggested Problems:

13, 15, 21, 25, 31