PHYSICS AND MEASUREMENTS

Physics is the most basic of the sciences. It deals with the behavior and structure of matter. The field of physics is usually divided into classical physics which includes motion, fluids, heat, sound, light, electricity, and magnetism; and modem physics which includes the topics of relativity, atomic structure, condensed matter, and nuclear physics, elementary particles, and cosmology and astrophysics. We will cover all these topics in this tutorial, beginning with motion (or mechanics, as it is often called) and ending with the most recent results in our study of the cosmos. An understanding of physics is crucial for anyone making a career in science or technology. Engineers, for example, must know how to calculate the forces within a structure to design it so that it remains standing (Fig. 1-la). Indeed, in our next tutorials, we will see a worked-out Example of how a simple physics calculation or even intuition based on understanding the physics of forces would have saved hundreds of lives (Fig. 1-lb). We will see many examples in this tutorial of how physics is useful in many fields, and everyday life.

Figure 1a

Figure 1b

The Nature of Physics

Physics is an experimental science. Physicists observe the phenomena of nature and try to find patterns and principles that relate to these phenomena. These patterns are called physical theories or when they are very well established and of broad use, physical laws, or principles. The development of physical theory requires creativity at every stage. The physicist must learn to ask appropriate questions, design experiments to try to answer the questions, and draw appropriate conclusions from the results. Legend has it that Galileo Galilei (1564-1642) dropped light and heavy objects from the top of the Leaning Tower of Pis to find out whether their rates of fall were the same or different. Galileo recognized that only experimental investigation could answer this question.

From examining the results of his experiments (which were much more sophisticated than in the legend), he

made the inductive leap to the principle, or theory, that the acceleration of a falling body is independent of its weight. The development of physical theories such as Galileo's is always a two-way process that starts and ends with observations or experiments. This development often takes an indirect path, with blind alleys, wrong guesses, and the discarding of unsuccessful theories in favor of more promising ones. Physics is not simply a collection of facts and principles; it is also the process by which we arrive at general principles that describe how the physical universe behaves. No theory is ever regarded as the final or ultimate truth. The possibility always exists that new observations will require that a theory be revised or discarded. It is like the physical theory that we can disprove a theory by finding behavior that is inconsistent with it, but we can never prove that a theory is always correct. Getting back to Galileo, suppose we drop a feather and a cannonball. They certainly do not fall at the same rate. This does not mean that Galileo was wrong; it means that his theory was incomplete.

If we drop the feather and the cannonball in a vacuum to eliminate the effects of the air, then they do fall at the same rate. Galileo's theory has a range of validity: It applies only to objects for which the force exerted by the air (due to air resistance and buoyancy) is much less than the weight. Objects like feathers or parachutes are clearly outside this range. Every physical theory has a range of validity outside of which it is not applicable. Often a new development in physics extends a principle's range of validity. Galileo's analysis of falling bodies was greatly extended half a century later by Newton's laws of motion and law of gravitation.

Standards of Length, Mass, and Time

The measurement of any quantity is made relative to a particular standard or unit, and this unit must be specified along with the numerical value of the quantity. For example, we can measure the length in British units such as inches, feet, or miles, or in the metric system in centimeters, meters, or kilometers. To specify that the length of a particular object is 18.6 is meaningless. The unit must be given; for clearly, 18.6 meters is very different from 18.6 inches or 18.6 millimeters.

For any unit we use, such as the meter for distance or the second for time, we need to define a **standard** that defines exactly how long one meter or one second is. Standards must be chosen that are readily reproducible so that anyone needing to make a very accurate measurement can refer to the standard in the laboratory.

Length

Length is a measure of distance. In the International System of Quantities, length is a quantity with dimension distance. In most systems of measurement, a base unit for length is chosen, from which all other units are derived. In the International System of Units (SI) system the base unit for length is the meter. Length is commonly understood to mean the most extended dimension of a fixed object. However, this is not always the case and may depend on the position the object is in. Various terms for the length of a fixed object are used, and these include height, which is the vertical length or vertical extent, and width, breadth, or depth. Height is used when there is a base from which vertical measurements can be taken. Width or breadth usually refers to a shorter dimension when the length is the longest one.

Depth is used for the third dimension of a three-dimensional object. Length is the measure of one spatial dimension, whereas area is a measure of two dimensions (length squared) and volume is a measure of three dimensions (length cubed).

Mass

The standard of mass, the kilogram (abbreviated kg), is defined to be the mass of a particular cylinder of platinum-iridium alloy kept at the International Bureau of Weights and Measures at Sevres, near Paris. An atomic standard of mass would be more fundamental, but at present, we cannot measure masses on an atomic scale with as much accuracy as on a macroscopic scale. The gram (which is not a fundamental unit) is 0.001 kilogram.

Time

Time in physics is defined by its measurement: time is what a clock reads. In classical, non-relativistic physics, it is a scalar quantity (often denoted by the symbol t) and, like length, mass, and charge, is usually described as a fundamental quantity. Time can be combined mathematically with other physical quantities to derive other concepts such as motion, kinetic energy, and time-dependent fields.

Unit Prefixes

Once we have defined the fundamental units, it is easy to introduce larger and smaller units for the same physical quantities. In the metric system, these other units are related to the fundamental units (or, in the case of mass, to the gram) by multiples of 10 or 1/10. Thus, one kilometer (1 km) is 1000 meters, and one centimeter (1 cm) is 1/1000 meters. We usually express multiples of 10 or to in exponential notation: $1000 = 10^3$, $1/1000 = 10^{-3}$, and so on. With this notation, 1 km = 10^3m and 1 cm =10^{-2}m. The names of the additional units are derived by adding a prefix to the name of the fundamental unit. For example, the prefix "kilo-," abbreviated k, always means a unit larger by a factor of 1000; thus

1 kilometer = 1 km = 10^3meters = 10^3m
1 kilogram = 1 kg = 10^3grams = 10^3g
1 kilowatt = 1 kW = 10^3watts = 10^3W

Length

1 nanometer = 1nm = 10^{-9}m
1 micrometer = 1*u*m = 10^{-6}m
1 millimeter = 1 mm = 10^{-3}m
1 centimeter = 1 cm = 10^{-2}m
1 kilometer = 1 km = 10^3

Dimensions and Dimensional Analysis

The word dimension has a special meaning in physics. It denotes the physical nature of a quantity. Whether a distance is measured in units of feet or meters or fathoms, it is still a distance. We say its dimension is length.

Quantity	Dimensions	SI Units
Area	L^2	m^2
Volume	L^3	m^3
Speed	L/T	m/s
Acceleration	L/T^2	m/s^2

The symbols we use in this tutorial to specify the dimensions of length, mass, and time are L, M, and T, respectively. We shall often use brackets [ ] to denote the dimensions of a physical quantity. For example, the symbol we use for speed in this tutorial is v, and in our notation, the dimensions of speed are written as $[v] = L/T$. As another example, the dimensions of area A are $[A] = L^2$. The dimensions and units of area, volume, speed, and acceleration are listed in the table above. The dimensions of other quantities, such as force and energy, will be described as they are introduced in the text.

In many situations, you may have to check a specific equation to see if it matches your expectations. A useful and powerful procedure called dimensional analysis can assist in this check because dimensions can be treated as algebraic quantities. For example, quantities can be added or subtracted only if they have the same dimensions. Furthermore, the terms on both sides of an equation must have the same dimensions. By following these simple rules, 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. To illustrate this procedure, suppose you are interested in an equation for the position *x* of a car at a time *t* if the car starts from rest at x = 0 and moves with constant acceleration a. The correct expression for this situation is Let us use dimensional analysis to check the validity of this expression. The quantity x on the left side has the dimension of length. For the equation to be dimensionally correct, the quantity on the right side must also have the dimension of length. We can perform a dimensional check by substituting the dimensions for acceleration, L/T^2, and time, T, into the equation. That is, the dimensional form of equation $x = 1/2at^2$ is $\mathbf{L = {}^{L}/_{T}{}^{2} \times T^2 = L}$

The dimensions of time cancel as shown, leaving the dimension of length on the right-hand side to match that on the left. A more general procedure using dimensional analysis is to set up an expression of the form

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

where n and m are exponents that must be determined and the symbol ∝ indicates a proportionality. This relationship is correct only if the dimensions of both sides are the same. Because the dimension of the left side is length, the dimension of the right side must also be length. That is,

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

Because the dimensions of acceleration are $^{L}/_{T^2}$ and the dimension of time is T, we have

$$\left(^{L}/_{T^2}\right)^{n} T^{m} = L^{1}T^{0} ==> \left(L^{n}T^{m-2n}\right) = L^{1}T^{0}$$

Example 1.1 Analysis of an Equation

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

Solution

Identify the dimensions of v from Table 1.1:

$$[v] = {}^{L}/_{T}$$

Identify the dimensions of v from Table 1.1 and multiply by the dimension of *t*:

$$[at] = {}^{L}/_{T^2} \times T = {}^{L}/_{T}$$

Therefore, v = at is dimensionally correct because we have the same dimensions on both sides. (If the expression were given as $v = at^2$, it would be dimensionally incorrect. Try it and see!)

Example 1.2 **Analysis of a Power Law**

Suppose we are told that the acceleration 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*.

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

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

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

Solve the two equations for *n*:

$$n = -1$$

Write the acceleration expression:

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

In this section 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* was in $\frac{km}{h}$ and you wanted an in m/s^2

Summary

Physics, like other sciences, is a creative endeavor. It is not simply a collection of facts. Important **theories** are created with the idea of explaining **observations**. To be accepted, theories are **tested** by comparing their predictions with the results of actual experiments. Note that, in general, a theory cannot be “proved” in an absolute sense.

Scientists often devise models of physical phenomena. A **model** is a kind of picture or analogy that helps to describe the phenomena in terms of something we already know. A **theory** often developed from a model, is usually deeper and more complex than a simple model.

A scientific **law** is a concise statement, often expressed in the form of an equation, which quantitatively describes a wide range of phenomena. **Measurements** play a crucial role in physics but can never be perfectly precise. It is important to specify the **uncertainty** of measurement either by stating it directly using the ± notation, and/or by keeping only the correct number of **significant figures**.

Physical quantities are always specified relative to a particular standard or **unit**, and the unit used should

always be stated. The commonly accepted set of units today is **Systeme International** (SI), in which the standard units of length, mass, and time are the **meter**, **kilogram**, and **second**.

time are the meter, kilogram, and second. When converting units, check all conversion factors for the correct cancellation of units. Making rough, **order-of-magnitude estimates** is a very useful technique in science as well as in everyday life.

The **dimensions** of a quantity refer to the combination of base quantities that comprise it. Velocity, for example, has dimensions of [length/time] or [L/T]. **Dimensional analysis** can be used to check a relationship for the correct form.

Tables

TABLE 1–2 Some Typical Time Intervals

Time Interval	Seconds (approximate)
Lifetime of very unstable subatomic particle	10^{-23} s
Lifetime of radioactive elements	10^{-22} s to 10^{28} s
Lifetime of muon	10^{-6} s
Time between human heartbeats	10^{0} s (= 1 s)
One day	10^{5} s
One year	3×10^{7} s
Human life span	2×10^{9} s
Length of recorded history	10^{11} s
Humans on Earth	10^{14} s
Life on Earth	10^{17} s
Age of Universe	10^{18} s

TABLE 1–3 Some Masses

Object	Kilograms (approximate)
Electron	10^{-30} kg
Proton, neutron	10^{-27} kg
DNA molecule	10^{-17} kg
Bacterium	10^{-15} kg
Mosquito	10^{-5} kg
Plum	10^{-1} kg
Human	10^{2} kg
Ship	10^{8} kg
Earth	6×10^{24} kg
Sun	2×10^{30} kg
Galaxy	10^{41} kg

TABLE 1–1 Some Typical Lengths or Distances (order of magnitude)

Length (or Distance)	Meters (approximate)
Neutron or proton (diameter)	10^{-15} m
Atom (diameter)	10^{-10} m
Virus [see Fig. 1–5a]	10^{-7} m
Sheet of paper (thickness)	10^{-4} m
Finger width	10^{-2} m
Football field length	10^{2} m
Height of Mt. Everest [see Fig. 1–5b]	10^{4} m
Earth diameter	10^{7} m
Earth to Sun	10^{11} m
Earth to nearest star	10^{16} m
Earth to nearest galaxy	10^{22} m
Earth to farthest galaxy visible	10^{26} m

TABLE 1–4 Metric (SI) Prefixes

Prefix	Abbreviation	Value
yotta	Y	10^{24}
zetta	Z	10^{21}
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
deka	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}
atto	a	10^{-18}
zepto	z	10^{-21}
yocto	y	10^{-24}

TABLE 1–5 SI Base Quantities and Units

Quantity	Unit	Unit Abbreviation
Length	meter	m
Time	second	s
Mass	kilogram	kg
Electric current	ampere	A
Temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd