Physics and Measurement

Chapter 1

Advice that should be of benefit to you

- Objectives:
  - To provide the student with a clear and logical presentation of the basic concepts and principles of physics and to strengthen an understanding of the concepts and principles through a broad range of interesting applications to the real world.
- How to Study:
  - You can best accomplish this goal by carefully reading the textbook before you attend your lecture on the covered material.
  - It is essential that you understand the basic concepts and principles before attempting to solve assigned problems.

Physics

- Fundamental Science
  - concerned with the basic principles of the Universe
  - foundation of other physical sciences
- Divided into five major areas
  - Classical Mechanics
  - Relativity
  - Thermodynamics
  - Electromagnetism
  - Optics
  - Quantum Mechanics

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

Theory and Experiments

- Like all other sciences, physics is based on experimental observations and quantitative measurements. The main objectives of physics are to identify a limited number of fundamental laws that govern natural phenomena and use them to develop theories that can predict the results of future experiments.

Natural phenomena

- To describe natural phenomena, we must make measurements.
- Each measurement is associated with a physical quantity, such as the length or mass of an object.
- standard for basic quantities must be defined with Units.

Quantities Used

- In mechanics, three *basic quantities* are used
  - Length, Mass, Time
- Will also use *derived quantities,* that can be expressed in terms of basic quantities
  - area (a product of two lengths),
  - speed (a ratio of a length to a time interval),
  - density (per unit volume) , …

1.1 Standards of Length, Mass, and Time

- SI – Systéme International
  - agreed to in 1960 by an international committee

Quantity	Unit name	Unit symbol
Length	Meter	m
Time	Second	s
Mass	Kilogram	kg
Temperature	Kelvin	K
Electric current	Ampere	A
Amount of substance	Mole	mol
Luminous intensity	Candela	cd

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Length

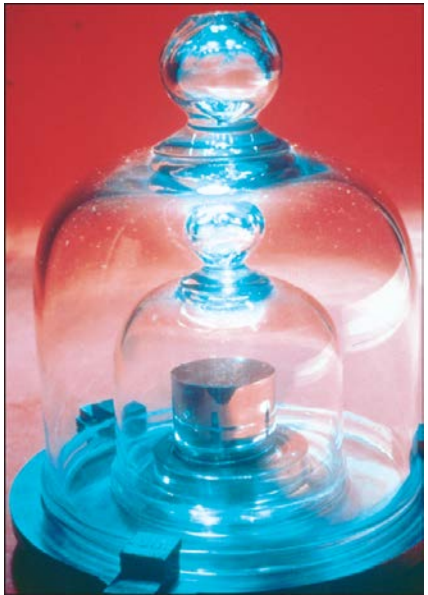
- Units
  - SI – meter, m
- Defined in terms of a meter – the distance traveled by light in vacuum during a time of 1/299 792 458 second.

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

- Units
  - SI – kilogram, kg
- the mass of a specific platinum–iridium alloy cylinder kept at the International Bureau of Weights and Measures at Sèvres, France.



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

- Units
  - SI – seconds, s
- One second is now defined as 9 192 631 770 times the period of vibration of radiation from the cesium-133

Time

Approximate Values of Some Time Intervals	
	Time Interval (s)
Age of the Universe	5×10^{17}
Age of the Earth	1.3×10^{17}
Average age of a college student	6.3×10^{8}
One year	3.2×10^{7}
One day	8.6×10^{4}
One class period	3.0×10^{3}
Time interval between normal heartbeats	8×10^{-1}
Period of audible sound waves	$\sim 10^{-3}$
Period of typical radio waves	$\sim 10^{-6}$
Period of vibration of an atom in a solid	$\sim 10^{-13}$
Period of visible light waves	$\sim 10^{-15}$
Duration of a nuclear collision	$\sim 10^{-22}$
Time interval for light to cross a proton	$\sim 10^{-24}$

Prefixes

- Prefixes correspond to powers of 10
- Each prefix has a specific name
- Each prefix has a specific abbreviation

Prefixes for Powers of Ten

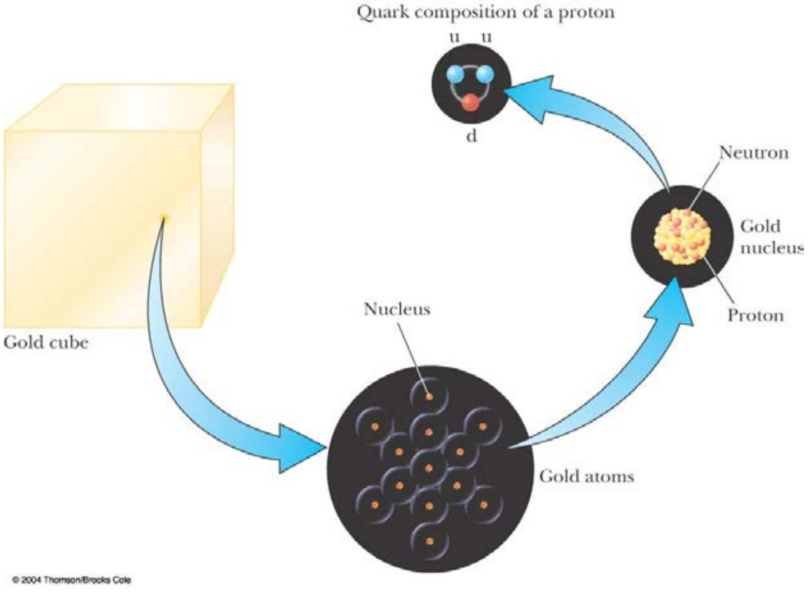
Power	Prefix	Abbreviation	Power	Prefix	Abbreviation
10^{-24}	yocto	y	10^{3}	kilo	k
10^{-21}	zepto	z	10^{6}	mega	M
10^{-18}	atto	a	10^{9}	giga	G
10^{-15}	femto	f	10^{12}	tera	T
10^{-12}	pico	p	10^{15}	peta	P
10^{-9}	nano	n	10^{18}	exa	E
10^{-6}	micro	μ	10^{21}	zetta	Z
10^{-3}	milli	m	10^{24}	yotta	Y
10^{-2}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

Prefixes, cont.

- The prefixes can be used with any base units
- They are multipliers of the base unit
- Examples:
  - $1\ mm = 10^{-3}\ m$
  - $1\ mg = 10^{-3}\ g$

1.2 Matter and Model Building

- If physicists cannot interact with some phenomenon directly, they often imagine a model for a physical system that is related to the phenomenon.



Models of Matter, cont

- Some Greeks thought matter is made of atoms
- JJ Thomson (1897) found electrons and showed atoms had structure
- Rutherford (1911) central nucleus surrounded by electrons

- Nucleus has structure, containing protons and neutrons
  - Number of protons gives atomic number
  - Number of protons and neutrons gives mass number
- Protons and neutrons are made up of quarks

Density

- Density is an example of a ***derived*** quantity
- It is defined as mass per unit volume

- Units are kg/m^3

$$\rho \equiv \frac{m}{V}$$

Quick Quiz 1.1 In a machine shop, two cams are produced, one of aluminum and one of iron. Both cams have the same mass. Which cam is larger? (a) The aluminum cam is larger. (b) The iron cam is larger. (c) Both cams are the same size.

Atomic Mass

- The atomic mass is the total number of protons and neutrons in the element
- Can be measured in ***atomic mass units***, u
  - 1 u = 1.6605387 x 10^{-27} kg

Basic Quantities and Their Dimension

- Dimension has a specific meaning – it denotes the physical nature of a quantity
- Dimensions are denoted with square brackets
  - Length [L]
  - Mass [M]
  - Time [T]

1.3 Dimensional Analysis

- Technique to check the correctness of an equation or to assist in deriving an equation
- Dimensions (length, mass, time, combinations) can be treated as algebraic quantities
  - add, subtract, multiply, divide
- Both sides of equation must have the same dimensions

Dimensional Analysis, cont.

- Cannot give numerical factors: this is its limitation
- Dimensions of some common quantities are given below

Table 1.6

Units of Area, Volume, Velocity, Speed, and Acceleration

System	Area (L^2)	Volume (L^3)	Speed (L/T)	Acceleration (L/T^2)
SI	m^2	m^3	m/s	m/s^2
U.S. customary	ft^2	ft^3	ft/s	ft/s^2

EXAMPLE 1.1 Analysis of an Equation

Show that the expression $v = at$, 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:

$$[v] = \frac{\mathrm{L}}{\mathrm{T}}$$

Identify the dimensions of a from Table 1.5 and multiply by the dimensions of t:

$$[at] = \frac{\mathrm{L}}{\mathrm{T}^{\not 2}}\not\mathrm{T} = \frac{\mathrm{L}}{\mathrm{T}}$$

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 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:

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

Solve the two equations for n:

$$n = -1$$

Write the acceleration expression:

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

In 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.

1.4 Conversion of Units

- When units are not consistent, you may need to convert to appropriate ones
- Units can be treated like algebraic quantities that can cancel each other out
- See the inside of the front cover for an extensive list of conversion factors
- Always include units for every quantity, you can carry the units through the entire calculation
- Multiply original value by a ratio equal to one

Conversion

$$1 \text{ mile} = 1\,609 \text{ m} = 1.609 \text{ km} \qquad 1 \text{ ft} = 0.304\,8 \text{ m} = 30.48 \text{ cm}$$

$$1 \text{ m} = 39.37 \text{ in.} = 3.281 \text{ ft} \qquad 1 \text{ in.} = 0.025\,4 \text{ m} = 2.54 \text{ cm (exactly)}$$

- Example

$$15.0\,\text{in} = ?\,\text{cm}$$

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

Quick Quiz 1.3 The distance between two cities is 100 mi. What is the number of kilometers between the two cities? (a) smaller than 100 (b) larger than 100 (c) equal to 100

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:

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

Convert seconds to hours:

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

The driver is indeed exceeding the speed limit and should slow down.

What If? What if the driver were from outside the United States and is familiar with speeds measured in km/h? What is the speed of the car in km/h?

Answer We can convert our final answer to the appropriate units:

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

Problems

- Problem (1)
- Which of the following equations are dimensionally correct?

(a) $v_f = v_i + ax$

(b) $y = (2\text{ m})\cos(kx)$, where $k = 2\text{ m}^{-1}$.

- Solution:

(a) since the units of [ax] are $[m^2 / s^2]$, while the units of [v] are [m/s].

(b) since the units of [y] are [m], and $\cos(kx)$ is dimensionless if [k] is in m^{-1} .

- Problem (2)
- Newton's law of universal gravitation is represented by

$$F = \frac{GMm}{r^2}$$

- Here F is the gravitational force exerted by one small object on another, M and m are the masses of the objects, and r is a distance. Force has the SI units kg·m/s^2. What are the SI units of the proportionality constant G?

Solution:

Inserting the proper units for everything except G,

$$\left[\frac{\text{kg m}}{\text{s}^2}\right] = \frac{G[\text{kg}]^2}{[\text{m}]^2}.$$

Multiply both sides by $[\text{m}]^2$ and divide by $[\text{kg}]^2$;

the units of G are $\boxed{\frac{\text{m}^3}{\text{kg} \cdot \text{s}^2}}$.

- Problem (3)

A rectangular building lot is 100 ft by 150 ft. Determine the area of this lot in m^2.

Solution:

We model the lot as a perfect rectangle to use Area = Length × Width. Use the conversion: $1\ \text{m} = 3.281\ \text{ft}$.

$$A = LW = (100\ \text{ft})\left(\frac{1\ \text{m}}{3.281\ \text{ft}}\right)(150\ \text{ft})\left(\frac{1\ \text{m}}{3.281\ \text{ft}}\right) = 1\,390\ \text{m}^2 = \boxed{1.39 \times 10^3\ \text{m}^2}.$$

- Problem (4)

A solid piece of lead has a mass of 23.94 g and a volume of 2.10 cm^3. From these data, calculate the density of lead in SI units (kg/m^3).

Solution:

Density is defined as mass per volume, in $\rho = \frac{m}{V}$.

We must convert to SI units in the calculation.

$$\rho = \frac{23.94\ \text{g}}{2.10\ \text{cm}^3}\left(\frac{1\ \text{kg}}{1\,000\ \text{g}}\right)\left(\frac{100\ \text{cm}}{1\ \text{m}}\right)^3 = \boxed{1.14 \times 10^4\ \text{kg/m}^3}$$

- Problem (5)
- At the time of this book's printing, the U. S. national debt is about \$6 trillion. (a) If payments were made at the rate of \$1 000 per second, how many years would it take to pay off the debt, assuming no interest were charged?
- (b) A dollar bill is about 15.5 cm long. If six trillion dollar bills were laid end to end around the Earth's equator, how many times would they encircle the planet? Take the radius of the Earth at the equator to be 6 378 km. (*Note* : Before doing any of these calculations, try to guess at the answers. You may be very surprised.)

Solution:

(a) $$\left(\frac{6\times 10^{12}\ \$}{1\,000\ \$/\text{s}}\right)\left(\frac{1\text{ h}}{3\,600\text{ s}}\right)\left(\frac{1\text{ day}}{24\text{ h}}\right)\left(\frac{1\text{ yr}}{365\text{ days}}\right)=\boxed{190\text{ years}}$$

(b) The circumference of the Earth at the equator is $2\pi\left(6.378\times 10^{3}\text{ m}\right)=4.01\times 10^{7}\text{ m}$. The length of one dollar bill is 0.155 m so that the length of 6 trillion bills is $9.30\times 10^{11}\text{ m}$. Thus, the 6 trillion dollars would encircle the Earth

$$\frac{9.30\times 10^{11}\text{ m}}{4.01\times 0^{7}\text{ m}}=\boxed{2.32\times 10^{4}\text{ times}}.$$

- Problem (6)
- The mean radius of the Earth is
- 6.37×10^6 m, and that of the Moon is
- 1.74×10^8 cm. From these data calculate (a) the ratio of the Earth's surface area to that of the Moon and (b) the ratio of the Earth's volume to that of the Moon. Recall that the surface area of a sphere is 4 r^2 and the volume of a sphere is .

Solution:

$$\text{(a)} \quad \frac{A_{\text{Earth}}}{A_{\text{Moon}}} = \frac{4\pi r_{\text{Earth}}^2}{4\pi r_{\text{Moon}}^2} = \left(\frac{r_{\text{Earth}}}{r_{\text{Moon}}}\right)^2 = \left(\frac{(6.37 \times 10^6 \text{ m})(100 \text{ cm/m})}{1.74 \times 10^8 \text{ cm}}\right)^2 = \boxed{13.4}$$

$$\text{(b)} \quad \frac{V_{\text{Earth}}}{V_{\text{Moon}}} = \frac{\frac{4\pi r_{\text{Earth}}^3}{3}}{\frac{4\pi r_{\text{Moon}}^3}{3}} = \left(\frac{r_{\text{Earth}}}{r_{\text{Moon}}}\right)^3 = \left(\frac{(6.37 \times 10^6 \text{ m})(100 \text{ cm/m})}{1.74 \times 10^8 \text{ cm}}\right)^3 = \boxed{49.1}$$