Physics for Scientists and Engineers,
10th edition, Raymond A. Serway and John W. Jewett, Jr.

Chapter 1:
Physics and Measurement

Customized by **Dr. H. Merabet, 2020**

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1.1. Standards of Length, Mass, and Time

We must define standards in measurements:

- ❑ Standard must be readily accessible and must possess some property that can be measured reliably
- ❑ Measurement standards used by different people in different places in the Universe must yield the same result
- ❑ Standards used for measurements must not change with time

To describe natural phenomena: One must make measurements of various aspects of nature:

- ❖Each measurement associated with a physical quantity, i.e., length of an object
- ❖Laws of physics are expressed as mathematical relationships among physical quantities

In mechanics, the three fundamental quantities are: length, mass, and time. All other quantities in mechanics can be expressed in terms of these three

In 1960, an international committee established a set of standards for the fundamental quantities of science: SI (Système International) Fundamental units:

- ❖ Length (meter)
- ❖ Mass (kilogram)
- ❖ Time (second)
- ❖ Temperature (kelvin)
- ❖ Electric current (ampere)
- ❖ Luminous intensity (candela)
- ❖ Amount of substance (mole)

Length

Length: distance between two points in space

- In 1120, the king of England decreed that the standard of length in his country would be named the yard and would be precisely equal to the distance from the tip of his nose to the end of his outstretched arm
    - This standard is NOT constant in time:
    - When a new king took the throne, length measurements changed!

- In 1799, legal standard of length in France became the meter (m)

- Current requirements of science and technology ⟶ Need more accuracy
- October 1983: meter redefined as distance traveled by light in vacuum during a time interval of **1/299 792 458** second

- Latest definition establishes that the **speed of light** in vacuum is precisely 299 792 458 m/s

- Valid throughout the Universe based on our assumption that light is the same everywhere
- Speed of light also allows us to define the **light-year**: Distance light travels through empty space in one year

Length

Length: distance between two points in space

TABLE 1.1 Approximate Values of Some Measured Lengths

	Length (m)
Distance from the Earth to the most remote known quasar	2.7×10^{26}
Distance from the Earth to the most remote normal galaxies	3×10^{26}
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

Mass of an object related to:

- ❖ Amount of material present in the object
- ❖ How much that object resists changes in its motion
- ❖ Mass is an inherent property of an object
- ❖ Independent of the object's surroundings and of method used to measure it

- SI fundamental unit of **mass (kilogram)**: **mass of a specific platinum–iridium alloy cylinder kept at the International Bureau of Weights and Measures at Sèvres, France**
  - Established in 1887 and has not been changed since that time
  - Platinum–iridium is an unusually stable alloy
  - Duplicate of the Sèvres cylinder is kept at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland (figure)

- Later we will discuss difference between mass and weight
- In introductory storyline: 1 kg $\approx$ 2.2 lb
  - Not correct to claim that a number of kilograms *equals* a number of pounds:
  - Units represent different variables
    - A kilogram is a unit of *mass*
    - A pound is a unit of *weight*

Mass

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}

a

Kilogram: **mass of a specific platinum–iridium alloy cylinder kept at the International Bureau of Weights and Measures at Sèvres, France**

Time

- Before 1967, the standard of time defined in terms of the mean solar day
    - Solar day: time interval between successive appearances of the Sun at the highest point it reaches in the sky each day
- The fundamental unit of a second (s) was defined as (1/60)(1/60)(1/24) of a mean solar day
    - Definition based on rotation of Earth → time standard is not universal
- 1967: second redefined in terms of atomic clock (figure):
    - 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**
- Note: *time* and *time interval* are different
- **Time**: description of an instant relative to a reference time
    - Example: t = 10.0 s refers to an instant 10.0 s after the instant we have identified as t = 0
    - A *time* of 11:30 a.m. means an instant 11.5 hours after our reference time of midnight
- **Time interval**: *duration*
    - Example: someone required 30.0 minutes to finish the task

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Powers of 10

- We can also use other units (e.g., millimeters and nanoseconds)
  - Examples
    - 10^{-3} m is equivalent to 1 millimeter (mm)
    - 10^{3} m corresponds to 1 kilometer (km)
    - 1 kilogram (kg) is 10^{3} grams (g)
    - 1 mega volt (MV) is 10^{6} volts (V)

- Length, mass, and time: ***fundamental quantities***
  - Most other variables are *derived* quantities: can be expressed as a mathematical combination of fundamental quantities
  - Examples:
    - *Area* (a product of two lengths)
    - *Speed* (a ratio of a length to a time interval)

Powers of 10

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			

Density

- Derived quantity: **density**
- Density (ρ) of any substance: *mass per unit volume:*

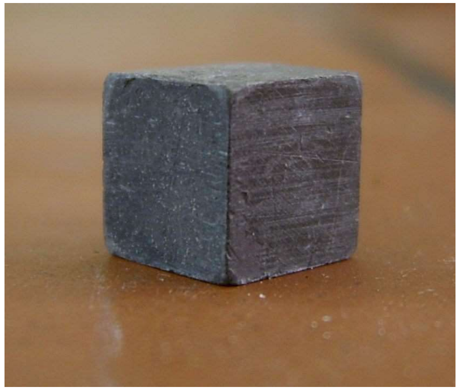
$$\rho \equiv \frac{m}{V}$$

- Density is a ratio of a mass to a product of three lengths
  - Examples:
    - Aluminum density: 2.70×10^3 kg/m^3
    - Iron density: 7.86×10^3 kg/m^3

- Extreme difference in densities:
  - Imagine holding a 10-centimeter (cm) cube of Styrofoam in one hand and a 10-cm cube of lead in the other

Styrofoam

Lead



1.2. Modeling and Alternative Representations

A model is a simplified substitute for the real problem that allows us to solve the problem in a relatively simple way.

Two primary conditions for using particle model:

1. Size of the actual object of no consequence in analysis of its motion.
2. Any internal processes occurring in object of no consequence in analysis of its motion.

Thus we replace any extended object by particle:

particle model

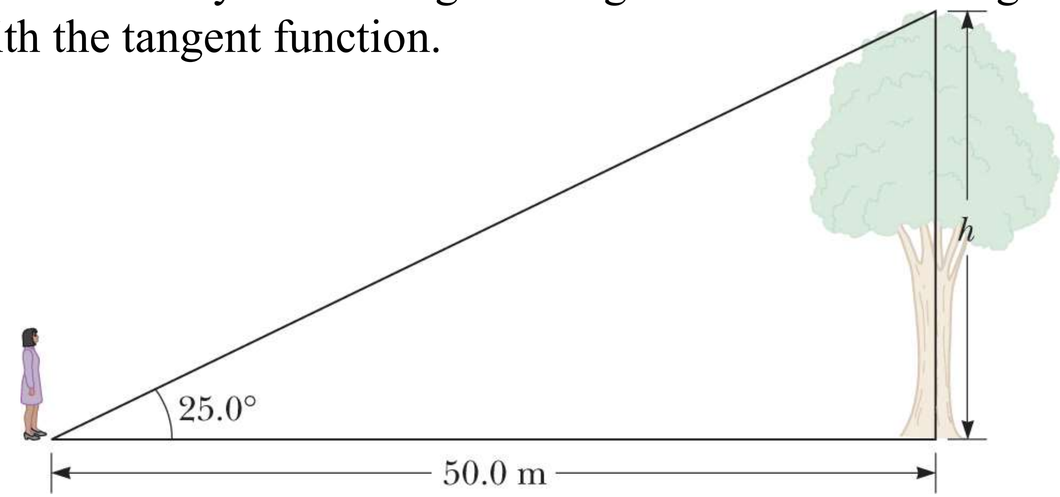
Example 1.1: Finding the Height of a Tree

You wish to find the height of a tree but cannot measure it directly. You stand 50.0 m from the tree and determine that a line of sight from the ground to the top of the tree makes an angle of 25.0 ° with the ground. How tall is the tree?

The figure shows the tree and a right triangle corresponding to the information in the problem superimposed over it. (We assume that the tree is exactly perpendicular to a perfectly flat ground.) In the triangle, we know the length of the horizontal leg and the angle between the hypotenuse and the horizontal leg. We can find the height of the tree by calculating the length of the vertical leg. We do so with the tangent function.

$$\tan\theta = \frac{\text{opposite side}}{\text{adjacent side}} = \frac{h}{50.0\ \text{m}}$$

$$\begin{aligned} h &= (50.0\ \text{m})\tan\theta \\ &= (50.0\ \text{m})\tan 25.0° \\ &= \boxed{23.3\ \text{m}} \end{aligned}$$



1.3 Dimension Analysis

- In physics: *dimension* denotes the physical nature of a quantity
    - Example: distance between two points can be measured in feet, meters, or furlongs (all different units for expressing the dimension of length)

- Dimensional analysis is a method of calculation utilizing a knowledge of units
    - Given units can be multiplied and divided to give the desired units

- Symbols to specify dimensions of length, mass, and time: L, M, and T
- Use brackets [ ] to denote dimensions of a physical quantity
    - Examples:
        - Symbol for speed = v
            - Dimensions of speed: $[v] = \mathrm{L/T}$
            - Dimensions of area A: $[A] = \mathrm{L}^2$

$$\text{speed: } [v] = \mathrm{L/T} \qquad \text{area: } [A] = \mathrm{L}^2$$

1.3 Dimension Analysis

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

[3]The *dimensions* of a quantity will be symbolized by a capitalized, nonitalic letter such as L or T. The *algebraic symbol* for the quantity itself will be an italicized letter such as L for the length of an object or t for time.

Table lists dimensions and units of area, volume, speed, and acceleration

1.3. Dimensional Analysis

- Can be used because dimensions can be treated as algebraic quantities
- Quantities can be added or subtracted only if they have same dimensions
- Terms on both sides of equation must have same dimensions

- Use dimensional analysis to determine whether an expression has the correct form
  - Any relationship can be correct only if dimensions on both sides of equation same

- Example: equation for position x of car at time t if car starts from rest at $x = 0$ and moves with constant acceleration a
  - Correct expression: $x = \frac{1}{2}at^2$
    - Quantity x on left side has dimension of length
  - For equation to be dimensionally correct: quantity on right side must also have dimension of length

- Perform dimensional check by substituting dimensions for acceleration and time into equation:
  - Dimensions of time cancel leaving dimension of length on right-hand side to match that on left

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

Example 1.2: Analysis of an Equation

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

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

$$[at] = \frac{\mathrm{L}}{\mathrm{T}^{\cancel{2}}}\,\cancel{\mathrm{T}} = \frac{\mathrm{L}}{\mathrm{T}}$$

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.

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

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

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

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

1.4. Conversion of Units

- Sometimes it is necessary to convert units from one measurement system to another (for example, from kilometers to meters).

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

$$1 \text{ mi} = 1\,609 \text{ m} = 1.609 \text{ km}$$

$$1 \text{ ft} = 0.304\,8 \text{ m} = 30.48 \text{ cm}$$

$$1 \text{ m} = 39.37 \text{ in.} = 3.281 \text{ ft}$$

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

1.4. Conversion of Units

- Like dimensions, units can be treated as algebraic quantities that can cancel each other.
- For Example we wish to convert 15.0 inch to centimeters:

$$1\text{ in.} = 2.54\text{ cm} \rightarrow \frac{2.54\text{ cm}}{1\text{ in.}}$$

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

- Ratio in parentheses = 1
- Unit “inch” in denominator cancels with the in original quantity
- Remaining unit: centimeter, our desired result

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?

$$\left(38.0\ \cancel{m}/\cancel{s}\right)\left(\frac{1\ \text{mi}}{1609\ \cancel{m}}\right)\left(\frac{60\ \cancel{s}}{1\ \cancel{\text{min}}}\right)\left(\frac{60\ \cancel{\text{min}}}{1\ \text{h}}\right) = 85.0\ \text{mi/h}$$

Yes, he is speeding!

Example 1.4:
Is He Speeding?

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

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

$$= 137\ \text{km/h}$$

1.5. Estimates and Order-of-Magnitude Calculations

- What is number of bits of data on typical Blu-ray Disc?
  - Give estimate, probably expressed in scientific notation

- Estimate may be made even more approximate by expressing it an *order of magnitude,* which is a power of ten:

  1. Express number in scientific notation, with multiplier of power of ten between 1 and 10 and a unit
  2. If multiplier $< 3.162 = \sqrt{10}$: order of magnitude of number = power of 10 in scientific notation.
  3. If multiplier $> 3.162 = \sqrt{10}$: order of magnitude = one larger than power of 10 in scientific notation

- Symbol ~ means "is on the order of"

$$0.0086 \text{ m} \sim 10^{-2} \text{ m}$$
$$0.0021 \text{ m} \sim 10^{-3} \text{ m}$$
$$720 \text{ m} \sim 10^{3} \text{ m}$$

- Usually, when order-of-magnitude estimate made: results reliable to within about a factor of 10
  - Inaccuracies caused by guessing too low for one number often canceled by other guesses that are too high
  - With practice guesstimates become better and better

Example 1.5: Breaths in a Lifetime

Estimate the number of breaths taken during an average human lifetime (70 years).

$$1\ \cancel{\text{yr}}\left(\frac{400\ \cancel{\text{days}}}{1\ \cancel{\text{yr}}}\right)\left(\frac{25\ \cancel{\text{h}}}{1\ \cancel{\text{day}}}\right)\left(\frac{60\ \cancel{\text{min}}}{1\,\text{h}}\right)=6\times10^{5}\ \text{min}$$

$$\text{number of minutes}=\left(70\ \text{yr}\right)\left(6\times10^{5}\ \text{min/yr}\right)$$

$$=4\times10^{7}\ \text{min}$$

$$\text{number of breaths}=\left(10\ \text{breaths/min}\right)\left(4\times10^{7}\ \text{min}\right)$$

$$=4\times10^{8}\ \text{breaths}$$

Example 1.5: Breaths in a Lifetime

What if the average lifetime were estimated as 80 years instead of 70? Would that change our final estimate?

$$(80 \text{ yr})\left(6\times10^{5} \text{ min/yr}\right) = 5\times10^{7} \text{ min}$$

$$(10 \text{ breaths/min})\left(5\times10^{7} \text{ min}\right) = 5\times10^{8} \text{ breaths}$$

on the order of 10^{9} breaths

1.6. Significant Figures

- Measured values known only to within the limits of experimental uncertainty
- Value of this uncertainty can depend on various factors:
  - Quality of apparatus
  - Skill of experimenter
  - Number of measurements performed
- Number of **significant figures** in measurement can be used to express something about uncertainty
  - Number of significant figures related to number of numerical digits used to express measurement

- Example: Measure radius of Blu-ray Disc using meterstick
  - Assume accuracy to which we can measure = ±0.1 cm
    - If radius measured to be 6.0 cm, we can claim only that its radius lies somewhere between 5.9 cm and 6.1 cm
  - Can say measured value of 6.0 cm has two significant figures:

$$(6.0 \pm 0.1)\ \text{cm}$$

    - Note that *significant figures include first estimated digit*

1.6. Significant Figures

- Nonzero numbers and zeros between nonzero numbers are always significant
- Zeros before the first nonzero digit, used to position decimal point, are not significant (Example: 0.0003 has one SF)
- Zeros may or may not be significant figures
- When zeros come after other digits, there is possibility of misinterpretation:
  - Zeros at the end of the number after a decimal point are significant.
  - Zeros at the end of a number before a decimal point are ambiguous (e.g., 10,300 g) Exponential notation can be used to clearly indicate whether zeros at the end of a number are significant.
- Example: Mass of object given as 1 500 g

$$1500 \text{ g} \rightarrow ? \text{ significant figures}$$

- Value ambiguous: don't know if last two zeros used to locate decimal point or whether they represent significant figures in measurement:

$$1.500 \times 10^3 \text{ g} \rightarrow 4 \text{ significant figures}$$

$$1.50 \times 10^3 \text{ g} \rightarrow 3 \text{ significant figures}$$

$$1.5 \times 10^2 \text{ g} \rightarrow 2 \text{ significant figures}$$

1.6. Significant Figures

- When quantities combined through multiplication, division, addition, subtraction:
  - Result must have appropriate number of significant figures.

When multiplying 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. The same rule applies to division.

1.6. Significant Figures

- Example: Find area of Blu-Ray Disc. The equation for area of circle given:

$$A = \pi r^2$$

$$\text{calculator answer: } 113.0973355$$

- Do not report result as 113 cm^2 $\cancel{113 \text{ cm}}$

- Result not justified because it has three significant figures, whereas radius only has two:

$$A = \pi r^2 = \pi (6.0 \text{ cm})^2 = \boxed{1.1 \times 10^2 \text{ cm}^2}$$

1.6. 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.

$$23.2 + 5.174 = 28.374$$

$$\rightarrow 23.2 \text{ has one decimal place} \rightarrow \text{sum} = 28.4$$

$$1.0001 + 0.0003 = 1.0004$$

$$1.002 - 0.998 = 0.004$$

1.6. Significant Figures

In this book, most of the numerical examples and end-of-chapter problems will yield answers having three significant figures. When carrying out estimation calculations, we shall typically work with a single significant figure.

last digit dropped > 5: increase last retained digit by 1: 1.356 → 1.35

last digit dropped = 5: increase last retained rounded to nearest even number: 1.345 → 1.34

last digit dropped < 5: leave last retained as is: 1.343 → 1.34

In long calculation involving multiple steps: important to delay rounding until final result → avoid error accumulation

Example 1.6: Installing a Carpet

A carpet is to be installed in a rectangular room whose length is measured to be 12.71 m and whose width is measured to be 3.46 m. Find the area of the room.

$$12.71\ \mathrm{m} \times 3.46\ \mathrm{m} = 43.9766\ \mathrm{m}^2$$

$$3.46 \rightarrow 3\ \text{sig figs} \rightarrow A = 44.0\ \mathrm{m}^2$$