



Ch.1: Physics and Measurement

Physics 103: Classical Mechanics

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1. Mechanics

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1.1 What is Mechanics?

- It is the branch of physics that deals with the *motion* of objects and the *forces* acting on them.
- **WHY** is it important?
 - *Understand* and Describe how objects move and interact.
 - *Predict* the behavior of objects in various situations.
 - *Control* the motion of objects through varying physical parameters such as force, mass, and direction.

1.1 What is Mechanics?

- **WHERE** is it applied? *Everywhere!*
 - Astronomy: understanding planetary motion.
 - Engineering: designing structures and machines.
 - Computer Science: simulating physical systems for games and animations.
 - Everyday life: from driving a car to playing sports.

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2.1 What are Physical Quantities?

- *ANYTHING* that can be measured or calculated in physics is a physical quantity.
- Examples: time, length, speed, mass, force, energy, ... etc.
- Non-physical quantities: opinions, emotions, feelings, desires, qualities, etc. (not measurable in physics).
- Physics laws are expressed as mathematical relationships among physical quantities.

2.2 Basic and Derived Quantities in Mechanics?

- *Basic* quantities are fundamental physical quantities that *cannot* be defined in terms of other quantities.
- Three basic quantities in mechanics: length, mass, and time.
- *Derived* quantities are defined in terms of basic quantities (e.g., speed = distance/time).

2.3 How to report measurements?

- People has to agree on one standard for each physical quantity.
- In 1960, an international committee established a set of standards for the fundamental quantities of science. It is called the SI (System International)

Quantity	SI Unit
Length	meter (m)
Mass	kilogram (kg)
Time	second (s)

2.4 Length: What is a meter?

- Defined in 1799 as one ten-millionth the distance from equator to North Pole.

$$1 \text{ m} = \frac{\text{Distance from Equator to North Pole}}{10,000,000}$$

- Redefined in 1983 as the distance light travels in vacuum in $1/299,792,458$ seconds.

$$1 \text{ m} = \frac{\text{Distance light travels in vacuum}}{299,792,458}$$

2.5 Time: What is a second?

- Before 1960, the standard of time was defined in terms of the mean solar day for the year 1900. The second was defined as:

$$\text{Second} = \text{Mean Day} \times \frac{1}{24} \times \frac{1}{60} \times \frac{1}{60}.$$

- In 1967, the second was redefined using atomic clocks, based on cesium-133 atom vibrations.

$$1s = (9,192,631,770) \text{ Cesium-133 atom cycle}$$



2.6 Mass: What is a kilogram?

- The SI unit of mass, 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.
- This mass standard was established in 1887 and has not been changed since that time because platinum-iridium is an unusually stable alloy.



2.7 How to express large and small numbers?

Prefix	Multiplier
Giga (G)	10^9
Mega (M)	10^6
Kilo (k)	10^3
Centi (c)	10^{-2}
Milli (m)	10^{-3}
Micro (μ)	10^{-6}
Nano (n)	10^{-9}

- $100,000 \text{ g} \Rightarrow 100 \times 10^3 \text{ g} \Rightarrow 100 \text{ kg}$.
- $0.001 \text{ m} \Rightarrow 1 \times 10^{-3} \text{ m} \Rightarrow 1 \text{ mm}$.

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3.1 Every Physical Quantity has a Dimension!

- Dimensions denote the physical nature of quantities,

$$\text{Speed} = [v] = \frac{L}{T} = \frac{\text{Unit of Length}}{\text{Unit of Time}}.$$

Quantity	Dimensions	Quantities	Dimension
Length	L	Mass	M
Time	T	Area	L^2
Volume	L^3	Speed	L/T
Acceleration	L/T^2	Force	$[\text{Mass}] \times [\text{Acceleration}]$

3.1 Every Physical Quantity has a Dimension!

- Different physical quantities have different dimensions and they cannot be added or subtracted.

$$L + T \quad \text{✗ Wrong}$$

3.2 Two main uses for dimensional analysis

- Use 1: Checking the consistency (correctness) of equations
- Use 2: Setting up (developing) new expressions

3.3 Use 1: Checking the Consistency of Equations

Dimensions are used to check the consistency of equations.

$$[\text{Speed}] = \frac{[\text{Distance}]}{[\text{Time}]}$$

$$L/T = \frac{L}{T} \quad \checkmark$$

But,

$$[\text{Speed}] = [\text{Distance}] * [\text{Time}]$$

$$L/T = L * T \quad \times \text{Wrong}$$

3.3 Use 1: Checking the Consistency of Equations

Example 3.1

Verify using dimensional analysis that the equation

$$x = \frac{1}{2}at^2,$$

is dimensionally correct, where x is the position, a is the acceleration, and t is the time.

Solution 3.1

- Dimension of x is L .
- Dimensions of a are L/T^2 .
- Dimensions of t is T .
- The right side becomes:
 $[\frac{1}{2}at^2] = (L/\cancel{T^2}) \cdot (\cancel{T^2}) = L$,
which matches the left side.

3.3 Use 1: Checking the Consistency of Equations

Example 3.2

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

Solution 3.2

- Dimension of v is L/T .
- Dimension of a is L/T^2 .
- Dimension of t is T .
- The right side becomes: $[at] = (L/T^2) \cdot T = L/T$, which matches the left side.

3.4 Use 2: Setting Up New Expressions

How? Three steps:

1. Identify the relevant physical quantities and their dimensions.

Example, $[x] = L, \quad [t] = T, \quad [v] = L/T$

2. Establish a relationship between the quantities to some unknown power $n, m, \dots$ for each quantity.

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

3. Use dimensional analysis to find the relationship and determine the values of the unknown powers.

$$LT^0 = (L/T)^n (T)^m = L^n T^{m-n} \implies n = m = 1 \implies x = vt$$

3.4 Use 2: Setting Up New Expressions

Example 3.3

Using dimensional analysis, find an expression for the distance x traveled by an object with constant acceleration a after a time t . Assume that the car starts from rest, so the initial velocity is zero.

3.4 Use 2: Setting Up New Expressions

Solution 3.3

- x is proportional to a^n and t^m , where n and m are constant exponents that we need to find by dimensional analysis. Therefore, we can write:

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

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,

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

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

- Therefore,

3.4 Use 2: Setting Up New Expressions

$$n = 1,$$
$$m - 2n = 0,$$

- Solving for m , we get: $m = 2$.
- Thus, the expression for x is:

$$x \propto at^2 = kat^2,$$

where k is a dimensionless constant.

3.4 Use 2: Setting Up New Expressions

Example 3.4

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.

3.4 Use 2: Setting Up New Expressions

Solution 3.4

- **Given:** $a \propto r^n v^m$.
- We know that:
 - The dimensions of acceleration are $[a] = L/T^2$
 - The dimensions of radius are $[r] = L$, and
 - The dimensions of speed are $[v] = L/T$.
- Thus, we can write the dimensional form of the equation as

$$a \propto r^n v^m = (L)^n (L/T)^m = L^{n+m} T^{-m}$$

$$[a] = L^1 T^{-2}$$

3.4 Use 2: Setting Up New Expressions

- For the equation to be dimensionally correct, the dimensions on both sides must match. Therefore, we have the following system of equations:

$$n + m = 1$$

$$-m = -2$$

From the second equation, we find that $m = 2$. Substituting this value into the first equation gives us $n + 2 = 1$, or $n = -1$. Thus, the simplest form of the equation for the acceleration is

$$a \propto \frac{v^2}{r} = k \frac{v^2}{r}$$

where k is a dimensionless constant of proportionality.

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4.1 Two Steps to Convert Units

- **Step 1:** *Identify* the conversion factor between the two units.
- Example conversion factors include:

$$1 \text{ mile} = 1609 \text{ meters}$$

$$1 \text{ foot} = 0.3048 \text{ meters}$$

$$1 \text{ inch} = 0.0254 \text{ meters}$$

- **Step 2:** *Multiply* the quantity by the conversion factor such that the original unit cancels out, leaving the desired unit.

4.1 Two Steps to Convert Units

Example 4.5

Convert 15 inches to centimeters.

Solution 4.5

- **Step 1:** Identify the conversion factors:

$$1 \text{ inch} = 0.0254 \text{ meters} = 2.54 \text{ centimeters}$$

- **Step 2:** Multiply the quantity by the conversion factors:

$$15.0 \text{ in.} = 15.0 \cancel{\text{ in.}} * \left(\frac{1 \cancel{\text{ in.}}}{1 \cancel{\text{ in.}}} \right) = 15.0 \text{ in.} \quad (\text{No change})$$

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

4.1 Two Steps to Convert Units

Example 4.6

A car is traveling at a speed of 38 m/s . Is this car exceeding the speed limit of 75 mi/h ?

4.1 Two Steps to Convert Units

Solution 4.6

- **Step 1:** Identify the conversion factors:

$$1 \text{ mile (mi)} = 1609 \text{ meters (m)}$$

$$1 \text{ hour (h)} = 3600 \text{ seconds (s)}$$

- **Step 2:** Convert the speed from m/s to mi/h:

$$\begin{aligned} 38 \text{ m/s} &= 38 \frac{\cancel{\text{m}}}{\cancel{\text{s}}} * \left(\frac{1 \text{ mi}}{1609 \cancel{\text{m}}} \right) * \left(\frac{3600 \cancel{\text{s}}}{1 \text{ h}} \right) \\ &= 38 * \left(\frac{1}{1609} \right) * (3600) \text{ mi/h} = 85.5 \text{ mi/h} \end{aligned}$$

- Therefore the car is exceeding the speed limit.

4.1 Two Steps to Convert Units

Example 4.7

From the previous example, what is the speed of the car in km/h?

4.1 Two Steps to Convert Units

Solution 4.7

- **Step 1:** Identify the conversion factors:

$$1 \text{ kilometer (km)} = 1000 \text{ meters (m)}$$

$$1 \text{ hour (h)} = 3600 \text{ seconds (s)}$$

- **Step 2:** Convert the speed from m/s to km/h:

$$\begin{aligned} 38 \text{ m/s} &= 38 \frac{\cancel{\text{m}}}{\cancel{\text{s}}} * \left(\frac{1 \text{ km}}{1000 \cancel{\text{m}}} \right) * \left(\frac{3600 \cancel{\text{s}}}{1 \text{ h}} \right) \\ &= 38 * \left(\frac{1}{1000} \right) * (3600) \text{ km/h} = 136.8 \text{ km/h} \end{aligned}$$

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5.1 Remember

- *Only* use SI units: *meter* (m), *kilogram* (kg), and *second* (s) in physics problems.
- Two main reasons for dimensional analysis:
 - To check the consistency of equations.
 - To set up expressions (equations).
- Two steps to convert units:
 - Identify (find) the conversion factor.
 - Multiply the quantity by the conversion factor to cancel out the original unit.

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6.1 Problems for Dimensional Analysis

Problem 6.1

Which of the following equations are dimensionally correct?

(a) $v_f = v_i + ax$

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

6.1 Problems for Dimensional Analysis

Answer 6.1

(a)

- The dimensions of the left side are $[v_f] = L/T$,
- the dimensions of the right side are

$$[v_i] + [a][x] = L/T + (L/T^2)L = L/T + L^2/T^2.$$

- The dimensions on the right side are not the same as those on the left side, so this equation **is not** dimensionally correct.
- Additionally, the right side has mixed dimensions, which is **NOT** allowed in dimensional analysis.

6.1 Problems for Dimensional Analysis

(b)

- The dimensions of the left side are $[y] = L$,

- The dimensions of the right side are

$$[2 \text{ m}][\cos(kx)] = L[\cos(kx)] = L,$$

because the cosine function is dimensionless.

- The dimensions on both sides are the same, so this equation is dimensionally correct.

6.2 Problems for Conversion of Units

Problem 6.2

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

6.2 Problems for Conversion of Units

Answer 6.2

- **Step 1:** Identify the conversion factors:

$$1 \text{ foot (ft)} = 0.3048 \text{ meters (m)}$$

- **Step 2:** Convert the dimensions from ft to m:

$$100 \text{ ft} = 100 \cancel{\text{ft}} \left(\frac{0.3048 \text{ m}}{1 \cancel{\text{ft}}} \right) = 30.48 \text{ m}$$

$$150 \text{ ft} = 150 \cancel{\text{ft}} \left(\frac{0.3048 \text{ m}}{1 \cancel{\text{ft}}} \right) = 45.72 \text{ m}$$

- The area in m^2 :

$$A = (30.48 \text{ m}) * (45.72 \text{ m}) = 1394 \text{ m}^2$$

6.2 Problems for Conversion of Units

Problem 6.3

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).

6.2 Problems for Conversion of Units

Answer 6.3

The density of a substance is defined as its mass divided by its volume:

$$\text{Density} = \frac{\text{mass}}{\text{volume}} = \frac{23.94g}{2.10\text{cm}^3}$$

To convert grams to kilograms and cubic centimeters to cubic meters, we use the following conversions:

$$1 \text{ kg} = 10^3 \text{ g}$$

$$1\text{m}^3 = (100 \text{ cm})^3 = 10^6 \text{ cm}^3$$

Substituting these values into the density equation gives us:

$$\text{Density} = \frac{23.94 \text{ g}}{2.10 \text{ cm}^3} \left(\frac{1 \text{ kg}}{10^3 \text{ g}} \right) \left(\frac{100 \text{ cm}}{1 \text{ m}} \right)^3 = 11400 \frac{\text{kg}}{\text{m}^3}.$$

6.2 Problems for Conversion of Units

Problem 6.4

One gallon of paint (volume= $3.78 \times 10^{-3} \text{ m}^3$) covers an area of 25 m^2 . What is the thickness of the paint on the wall?

6.2 Problems for Conversion of Units

Answer 6.4

The thickness of the paint can be calculated using the formula:

$$\begin{aligned}\text{Thickness} &= \frac{\text{Volume}}{\text{Area}} = \frac{3.78 \times 10^{-3} \text{ m}^3}{25 \text{ m}^2} \\ &= 1.512 \times 10^{-4} \text{ m} = 151.2 \mu\text{m} .\end{aligned}$$