Ch.1: Physics and Measurement

Physics 103: Classical Mechanics

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Outline

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1. Mechanics

2. Physical Quantities

3. Dimensional Analysis

4. Conversion of Units

5. Summary

6. Additional Examples

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?

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- *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:

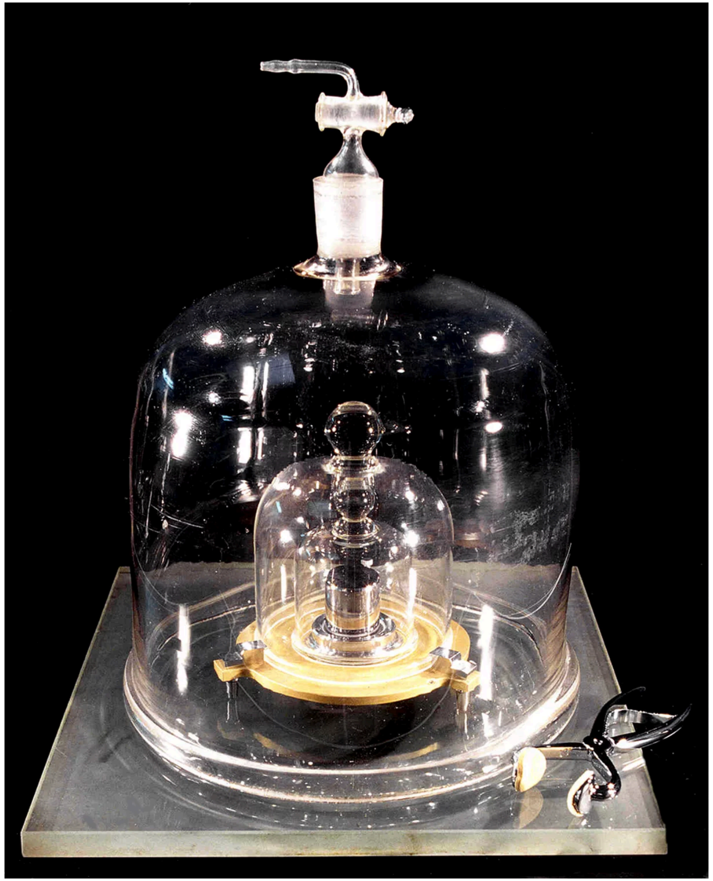
$$\text{Second} = \text{Mean Day} \times \frac{1}{24} \times \frac{1}{60} \times \frac{1}{60}.$$

- 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?

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

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}

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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	[Mass] × [Acceleration]

3.1 Every Physical Quantity has a Dimension!

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

$$L + T$$ ❌ **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,

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

$$L/T = L * T \quad ✗ \ \textbf{Wrong}$$

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 are L.
- Dimensions of a are L/T^2.
- Dimensions of t are 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

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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: $[at] = (L/T^{\cancel{2}}) \cdot \cancel{T} = L/T$, which matches the left side.

3.4 Use 2: Setting Up New Expressions

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How? Three steps:

1. Identify the relevant physical quantities and their dimensions.

$$\text{Example,} \qquad [x] = L, \quad [t] = T, \quad [v] = L/T$$

2. Establish a relationship between the quantities to some unknown power n, m, ... 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.

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

3.4 Use 2: Setting Up New Expressions

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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

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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,
$$[x] \propto [a^n t^m]$$
$$L = L^1 T^0 \propto \left(L/T^2\right)^n \; (T)^m = L^n \; T^{m-2n}$$
- 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.

- This expression is consistent with the kinematic equation for uniformly accelerated motion,

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

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

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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.

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

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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:

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

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

4.1 Two Steps to Convert Units

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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:

$$38 \text{ m/s} = 38 \, \frac{\cancel{m}}{\cancel{s}} * \left(\frac{1 \text{ mi}}{1609 \, \cancel{m}}\right) * \left(\frac{3600 \, \cancel{s}}{1 \text{h}}\right)$$

$$= 38 * \left(\frac{1}{1609}\right) * (3600) \text{ mi/h} = 85.5 \text{ mi/h}$$

- 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

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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:

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

$$= 38 * \left(\frac{1}{1000}\right) * (3600) \text{ km/h} = 136.8 \text{ km/h}$$

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

6.1 Problems for Dimensional Analysis

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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

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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

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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:

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

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

Substituting these values into the density equation gives us:

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

6.2 Problems for Conversion of Units

Problem 6.4

One gallon of paint (volume= 3.78×10^{-3} 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:

$$\text{Thickness} = \frac{\text{Volume}}{\text{Area}} = \frac{3.78 \times 10^{-3}\ \text{m}^3}{25\ \text{m}^2}$$

$$= 1.512 \times 10^{-4}\ \ \text{m} = 151.2\ \mu\text{m}.$$