PHY0101 and PHY/PEN 101 Mechanics, Chapter 1: Physics and Measurement

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Book: Serway Physics 9th Edition
(Serway, Jewett)

Mechanics: "Classical" Mechanics
"Classical" Physics:

"Classical" ≡ ≈ Before the 20th Century

The foundation of pure and applied macroscopic physics and engineering!

- *Newton's Laws* + Boltzmann's **Statistical Mechanics** (and Thermodynamics): ≈ Describe most of macroscopic world!
- However, at high speeds (**v ~ c**) we need

Special Relativity: (Early 20th Century: 1905)

- Also, for small sizes (atomic and smaller) we need

Quantum Mechanics: (1900 through ~ 1930)

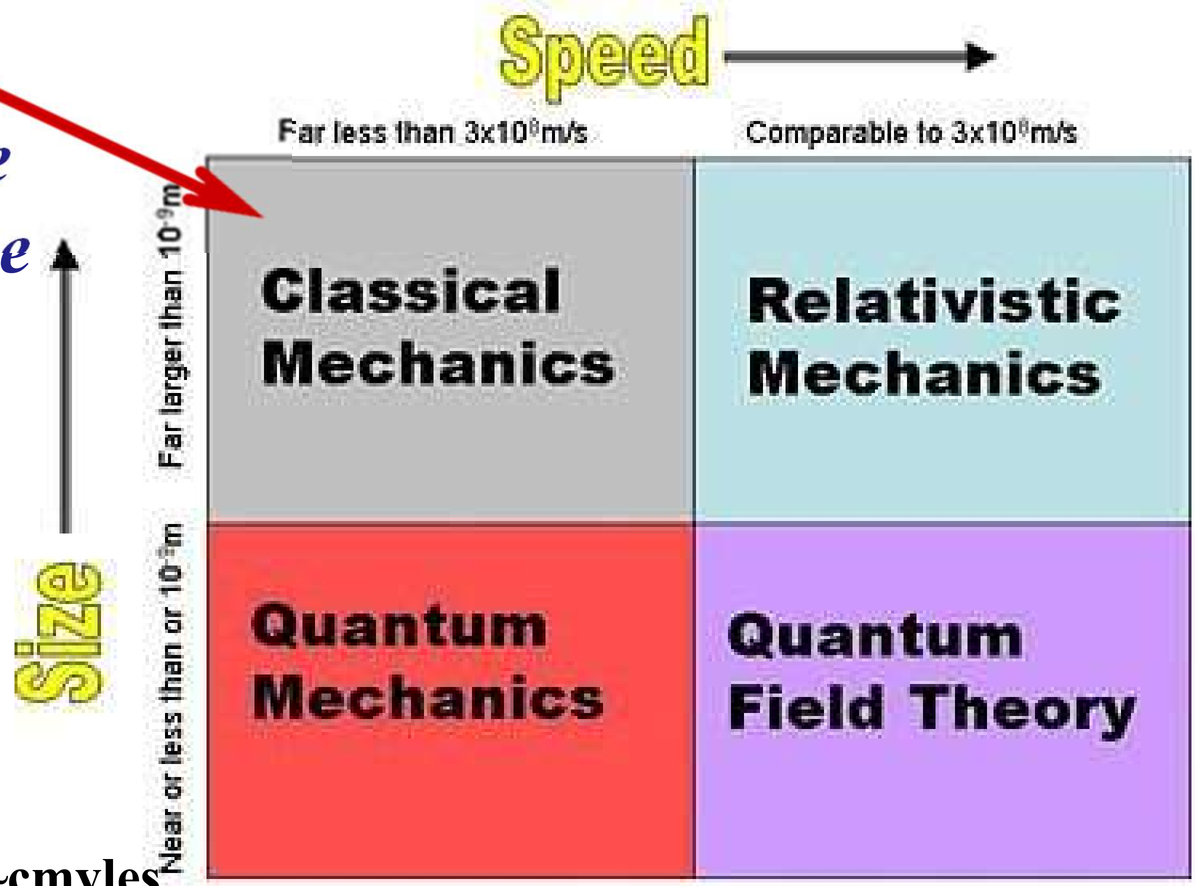
"Classical" Mechanics: (17th and 18th Centuries)

Still useful today!

"Classical" Mechanics

The physics in this course is ***limited to macroscopic objects*** moving at ***speeds v much, much smaller than the speed of light*** **$c = 3 \times 10^8$ m/s**. As long as $v << c$, our discussion will be valid.

So, we will work exclusively in the gray region in the figure.



Mechanics

- The science of ***HOW*** objects move (behave) under ***given forces***.
- (Usually) Does not deal with the ***sources*** of forces.
- Answers the question:

"Given the forces, how do objects move"?

Theory

- ***A Quantitative* (mathematical)*description*** of experimental observations.
- Not just ***WHAT*** is observed but ***WHY*** it is observed as it is and ***HOW*** it works the way it does.

Tests of Theories:

- **Experimental observations**:

  More experiments, more observation.

- **Predictions**:

  Made before observations & experiments.

Chapter 1 Measurement

- 1.1 Standards of Length, Mass, and Time
- 1.2 Matter and Model Building
- 1.3 Density and Atomic Mass
- 1.4 Dimensional Analysis
- 1.5 Conversion of Units
- 1.6 Estimates and Order-of-Magnitude Calculations
- 1.7 Significant Figures

1.1 Standards of Length, Mass, and Time

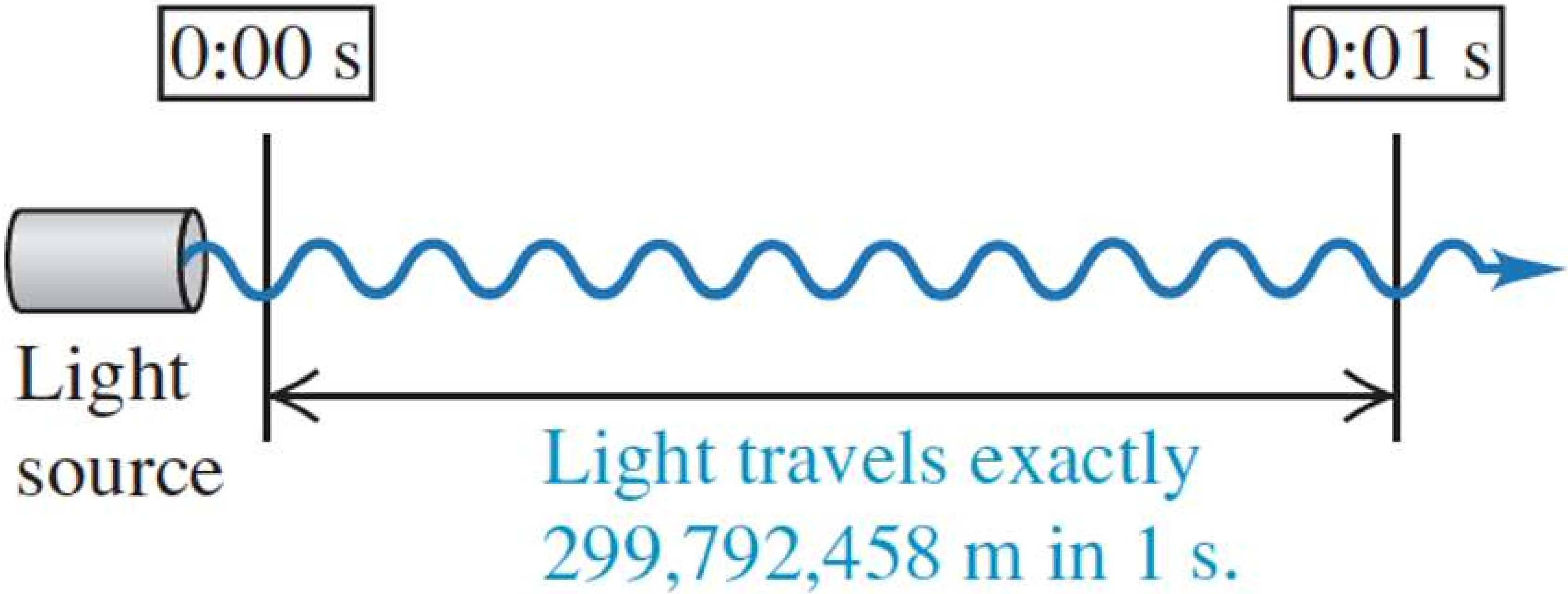
- In mechanics, the three basic quantities are length, mass and time. All other quantities in mechanics can be expressed in terms of these three.
- If we are to report the results of a measurement to someone who wishes to reproduce this measurement, a *standard* must be defined.
- In 1960, an international committee established a set of standards for the fundamental quantities of science. It is called the SI (Système International)

Fundamental Quantities and Their Units

Quantity	SI Unit	Abbreviation
Length	meter	m
Mass	kilogram	kg
Time	second	s
Temperature	kelvin	K
Electric Current	ampere	A
Luminous Intensity	candela	cd
Amount of Substance	mole	mol

Length

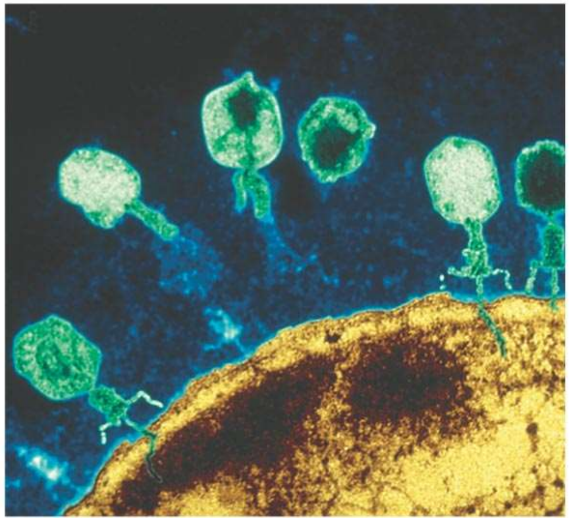
- *Length* is the distance between two points in space
- Units
  - SI – meter, m
- Defined in terms of a meter – the distance traveled by light in a vacuum during during a time of 1/299 792 458 second



In October 1983, the meter (m) was redefined as 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 (M 31, the Andromeda galaxy)	2×10^{22}
Distance from the Sun to the nearest star (Proxima Centauri)	4×10^{16}
One lightyear	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	$\sim 10^{-15}$



Virus: 10^{-7} m

Height of
Everest: 10^{4} m

Mass

- Units
  - SI – kilogram, kg
- Previously defined in terms of a kilogram, based on the mass of a specific platinum–iridium alloy cylinder kept at the International Bureau of Weights and Measures at Sèvres, France.
- In 20 Mayıs 2019 the definition has changed.

Standard Kilogram at Sèvres, France

- The problem with this definition was its imprecision. It was not based on unchanging properties of the universe.
- Light speed, on the other hand, is unchanging. By 1983, physicists had gotten really good at measuring the speed of light.
- Every unit in the Planck constant is defined by an unchanging force of nature. Planck's constant is equal to 6.626069934 x 10^{-34} $kg.m^2/s$ and uncertainty was just 13 parts per billion.

- The new definition relates the kilogram to the equivalent mass of the energy of a photon given its frequency, via the Planck constant.
- kg is defined by taking the fixed numerical value of the Planck constant h to be $6.62607015 \times 10^{-34}$ when expressed in the unit $J \cdot s$, which is equal to $kg \cdot m^2 \cdot s^{-1}$, where the metre and the second are defined in terms of c and $\Delta \nu_{Cs}$.

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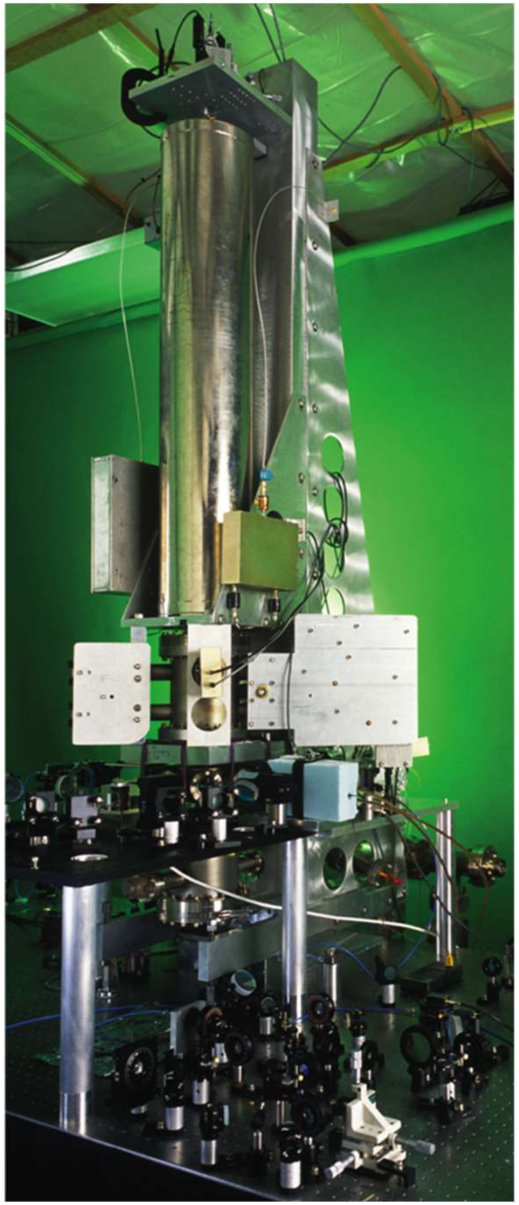
Time

- Units
  - seconds, s
- Defined in terms of the oscillation of radiation from a cesium atom
- In 1967 the second (s) is defined as 9 192 631 770 times the period of vibration of radiation from the cesium atom.

Standard Second

A cesium fountain atomic clock. This clock will ***neither gain nor lose a second in 20 million years!***



Source of figure: NIST Primary Frequency Standards and the Realization of the SI Second

Similar Information on Typical Times

Approximate Values of Some Time Intervals

	Time Interval (s)
Age of the Universe	4×10^{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	$\sim 10^{-24}$

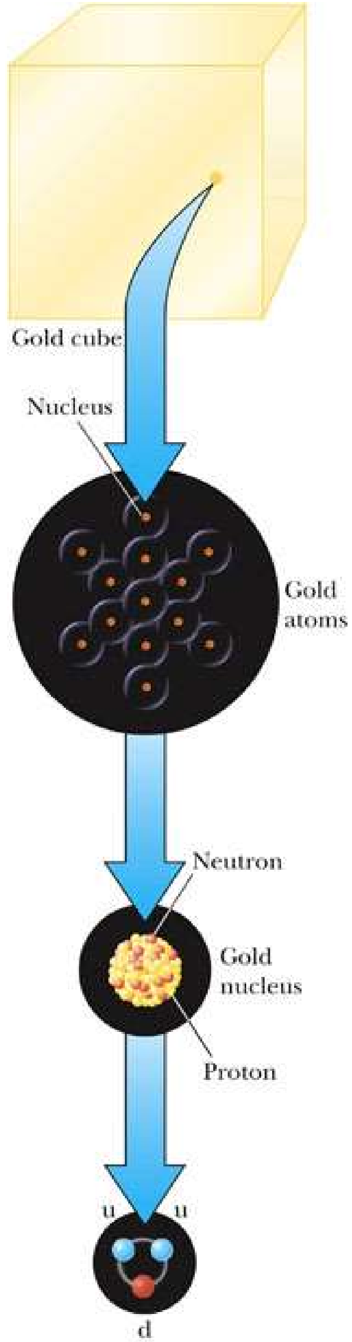
US Customary System

- Still used in the US, but we will use **SI**

Quantity	Unit
Length	foot
Mass	slug
Time	second

Models of Matter

- Some Greeks thought matter is made of atoms
  - In Greek, atomos means "not sliceable."
  - JJ Thomson (1897) found electrons and showed atoms had structure
- Rutherford (1911) central nucleus surrounded by electrons



Quark composition of a proton

Models of Matter, cont

- 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

1.3 Density and Mass

- **Density:** *mass per unit volume*

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

For example, aluminum has a density of 2.70 g/cm^3, and lead has a density of 11.3 g/cm^3. Therefore, a piece of aluminum of volume 10.0 cm^3 has a mass of 27.0 g, whereas an equivalent volume of lead has a mass of 113 g.

An atomic mass unit is a physical constant equal to one-twelfth of the mass of an unbound atom of carbon-12.

1 atomic mass unit (u): 1 u =1.660 538 7 x 10^{-27} kg.

Example How many Atoms in the Cube? A solid cube of aluminum (density 2.70 g/cm^3) has a volume of 0.200 cm^3. It is known that 27.0 g of aluminum contains 6.02x10^{23} atoms. How many aluminum atoms are contained in the cube?

$$m = \rho V = (2.70\ \text{g}/\cancel{\text{cm}^3})(0.200\ \cancel{\text{cm}^3}) = 0.540\ \text{g}$$

$$\frac{0.540\ \text{g}}{27.0\ \text{g}} = \frac{N_{\text{sample}}}{6.02 \times 10^{23}\ \text{atoms}}$$

$$N_{\text{sample}} = \frac{(0.540\ \text{g})(6.02 \times 10^{23}\ \text{atoms})}{27.0\ \text{g}}$$

$$= 1.20 \times 10^{22}\ \text{atoms}$$

1.4 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
- Any relationship can be correct only if the dimensions on both sides of the equation are the same
- Cannot give numerical factors: this is its limitation

Dimensional Analysis, example

- Given the equation: $x = ½ at^2$
- Check dimensions on each side:

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

- The T^2's cancel, leaving L for the dimensions of each side
  - The equation is dimensionally correct
  - There are no dimensions for the constant

Dimensional analysis to determine a power law

- Determine powers in a proportionality
  - Example: find the exponents in the expression $x \propto a^m t^n$

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

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

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

n=1 $m - 2n = 0$

$$x \propto at^2$$

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

Example 3 Analysis of 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

$$a = kr^n v^m \quad \Rightarrow \quad \frac{\mathrm{L}}{\mathrm{T}^2} = \mathrm{L}^n \left(\frac{\mathrm{L}}{\mathrm{T}}\right)^m = \frac{\mathrm{L}^{n+m}}{\mathrm{T}^m}$$

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

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

1.5 Conversion of Units

- Sometimes it is necessary to convert units from one measurement system to another, or to convert within a system, for example, from kilometers to meters.

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

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

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

1.6 Estimates and Order-of-Magnitude Calculations

- It is often useful to compute an approximate answer to a given physical problem even when little information is available.
  - may need to modify assumptions if more precise results are needed
- Order of magnitude is the power of 10 that applies

$$0.008\,6 \sim 10^{-2} \qquad 0.002\,1 \sim 10^{-3} \qquad 720 \sim 10^{3}$$

$3{,}000\ m = 3 \times 1{,}000\ m$

$= 3 \times 10^3\ m = 3\ km$

$1{,}000{,}000{,}000 = 10^9 = 1G$

$1{,}000{,}000 = 10^6 = 1M$

$1{,}000 = 10^3 = 1k$

141 kg = ? g

1 GB = ? Byte = ? MB

10^x	Prefix	Symbol
x=18	exa	E
x=15	peta	P
x=12	tera	T
x=9	giga	G
x=6	Mega	M
x=3	kilo	k
x=2	hecto	h
x=1	deca	da

Some Prefixes for Powers of Ten

Power	Prefix	Abbreviation
10^{-24}	yocto	y
10^{-21}	zepto	z
10^{-18}	atto	a
10^{-15}	femto	f
10^{-12}	pico	p
10^{-9}	nano	n
10^{-6}	micro	μ
10^{-3}	milli	m
10^{-2}	centi	c
10^{-1}	deci	d

Powers of 10 (Scientific Notation)

- It is common to express very large or very small numbers using powers of 10 notation.

Examples

$39{,}600 = 3.96 \times 10^{4}$

(moved decimal 4 places to left)

$0.0021 = 2.1 \times 10^{-3}$

(moved decimal 3 places to right)

PLEASE USE SCIENTIFIC NOTATION!

Example 1.5 Breaths in a Lifetime

Estimate the number of breaths taken during an average life span.

Solution

The number of minutes in a year is approximately

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

Thus, in 70 years there will be

$$(70\ \ \text{yr})(6\times10^{5}\ \text{min/yr}) = 4\times10^{7}\ \text{min}.$$

At a rate of 10 breaths/min, an individual would take

4×10^{8} breaths

on the order of 10^{9} breaths

Measurement Uncertainty; Significant Figures

No measurement is exact; there is always some ***uncertainty*** due to limited instrument accuracy & difficulty reading results.

It is common to state this precision (when known).

The photograph to the left illustrates this – it would be difficult to measure the width of this.

- Consider a simple measurement of the width of a board. Find **23.2 cm**.
- However, measurement is only accurate to **0.1** cm (estimated).

$\Rightarrow$ We write the width as

(23.2 ± 0.1) cm

± 0.1 cm ≡ *Experimental uncertainty*

- **Percent Uncertainty:**

$$\pm (0.1/23.2) \times 100 \approx \pm 0.4\%$$

Significant Figures

Significant Figures ("sig figs") ≡

The number of significant figures is the number of reliably known digits in a number.

It is usually possible to tell the number of significant figures by the way the number is written:

23.21 cm has 4 significant figures

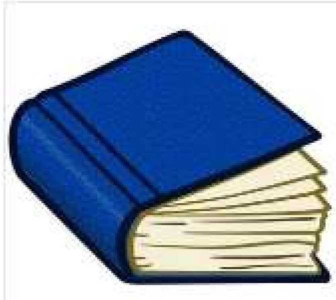
0.062 cm has 2 significant figures

(initial zeroes don't count)

80 km is ambiguous:

it could have 1 or 2 significant figures.

If it has 3, it should be written 80.0 km.



- If we were to claim the area of a book is (5.5 cm)(6.4 cm)=35.2 cm^2, our answer would be unjustifiable because it contains three significant figures, which is greater than the number of significant figures in either of the measured quantities.

When multiplying or dividing numbers:

The number of sig figs in the result ≡ the same number of sig figs as the number used in the calculation with the fewest sig figs.

When adding or subtracting numbers:

The answer is no more accurate than the least accurate number used.

Rounding

- Last retained digit is increased by 1 if the last digit dropped is greater than 5
- Last retained digit remains as it is if the last digit dropped is less than 5
- If the last digit dropped is equal to 5, the retained digit should be rounded to the nearest high even number
- Saving rounding until the final result will help eliminate accumulation of errors

- **Example**
  - **Area of a board:**

    dimensions 11.3 cm × 6.8 cm
  - **Area = (11.3) × (6.8) = 76.84 cm^2**

    11.3 has 3 sig figs , 6.8 has 2 sig figs

    ⇒ **76.84 has too many sig figs!**

    Proper number of sig figs in answer = 2

    ⇒ Round off 76.84 and keep only 2 sig figs

⇒ **Reliable answer for area = 77 cm^2**

$$\frac{0.745x2.2}{3.885} = 0.42187902 \quad \Rightarrow \quad \frac{0.745x2.2}{3.885} = 0.42$$

$$1.32578 \times 10^{7} \times 4.11 \times 10^{-3} = 5.4489558 \times 10^{4}$$

$$\Downarrow$$

$$1.32578 \times 10^{7} \times 4.11 \times 10^{-3} = 5.45 \times 10^{4}$$

Summary

- The three fundamental physical quantities of mechanics are length, mass and time, which in the SI system have the units meter (m), kilogram (kg) and second (s), respectively.
- The method of **dimensional analysis** is very powerful for solving physics problems.
- Units in physical equations should always be consistent.
- When you compute a result from several measured numbers, each of which has a certain accuracy, you should give the result with the correct number of significant figures.

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