Physical Principles in Biology
Biology 3550
Spring 2025

Lecture 2:

Introduction to Measurement and Units

Wednesday, 8 January 2025

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Clicker Question #1

Why are you taking this class? (Choose one.)

A) To broaden my background in science

B) To satisfy a requirement for my major

C) To satisfy the QI (quantitative intensive) requirement

D) Other graduation requirement

Clicker Question #2

When do you expect to graduate?

A) Spring 2025

B) Fall 2025

C) Spring 2026

D) Fall 2026

E) Someday

Clicker Question #3

What do you hope to do after graduating?

A) Work in a science-related area

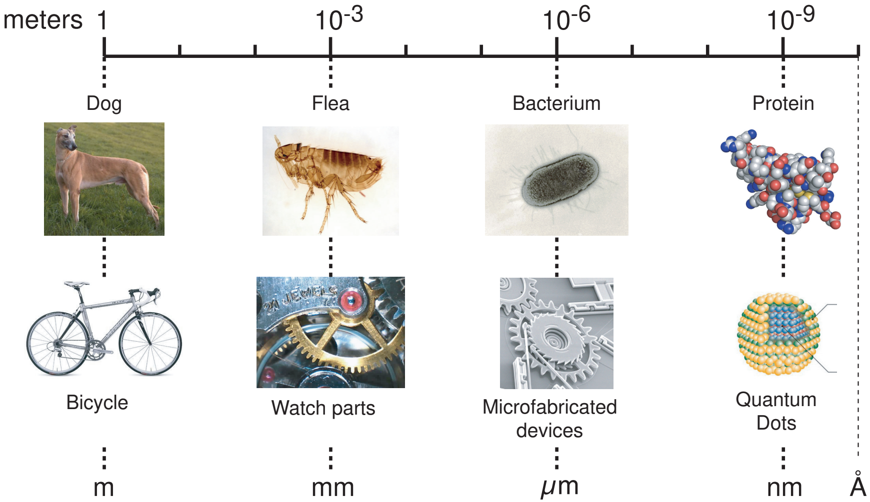
B) Work in an area unrelated to science

C) Go to graduate school

D) Go to medical school or other professional school.

E) Something else entirely!

Length Scales for Biological and Human-manufactured Objects



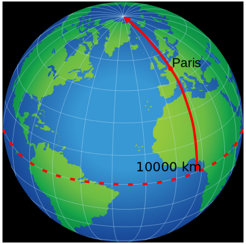
A Classic Movie About the Range of Length Scales

- Created by Charles and Ray Eames in 1977 for IBM
- https://www.eamesoffice.com/the-work/powers-of-ten-brochure/
- https://www.youtube.com/watch?v=0fKBhvDjuy0

Original Metric System – France, 1795

Defined two basic units:

- meter (*mètre*): One ten-millionth of the distance from the Equator to the North Pole along the meridian passing through Paris.



- gram (*gramme*): Mass of one cm^3 of pure water at the melting temperature of ice.

https://en.wikipedia.org/wiki/Metric_system

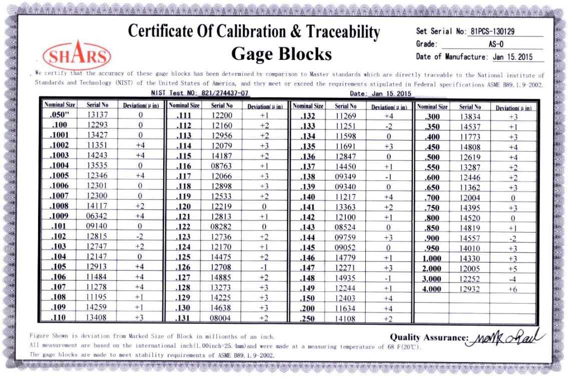
Original Reference Objects for Meter and Kilogram

- *Métre des Archives* (1799)
  - Platinum bar based on measurement of the meridian and placed in the French National Archives.
  - Actually short of the definition based on the meridian, by 0.2 mm, but used anyway.
  - Subsequently replaced by other metal bars.
  - Eventually (1988) replaced by a definition based on the speed of light: Distance travelled by light in vacuum in 1/299,792,458 of a second.
- *Kilogramme des Archives* (1799)
  - Cylinder of platinum based on the mass of water and placed in the French National Archives.
  - Replaced in 1889 by the international prototype kilogram (IPK), made of platinum-iridium alloy.
  - IPK was the standard definition of the kilogram until 2019!

International Prototypes for kg and meter (British versions)

Photograph from http://www.metric.org.uk

A Certificate of Traceability



SHARS

Certificate Of Calibration & Traceability

Gage Blocks

Set Serial No: 81PCS-130129
Grade: AS-0
Date of Manufacture: Jan 15. 2015

We certify that the accuracy of these gage blocks has been determined by comparison to Master standards which are directly traceable to the National institute of Standards and Technology (NIST) of the United States of America, and they meet or exceed the requirements stipulated in Federal specifications ASME B89.1.9-2002.

NIST Test NO: 821/274437-07 Date: Jan 15. 2015

Nominal Size	Serial No	Deviation(μ in)	Nominal Size	Serial No	Deviation(μ in)	Nominal Size	Serial No	Deviation(μ in)	Nominal Size	Serial No	Deviation(μ in)
.050"	13137	0	**.111**	12200	+1	**.132**	11269	+4	**.300**	13834	+3
.100	12293	0	**.112**	12160	+2	**.133**	11251	-2	**.350**	14537	+1
.1001	13427	0	**.113**	12956	+2	**.134**	11598	0	**.400**	11773	+3
.1002	11351	+4	**.114**	12079	+3	**.135**	11691	+3	**.450**	14808	+4
.1003	14243	+4	**.115**	14187	+2	**.136**	12847	0	**.500**	12619	+4
.1004	13535	0	**.116**	08763	+1	**.137**	14450	+1	**.550**	13287	+2
.1005	12346	+4	**.117**	12066	+3	**.138**	09349	-1	**.600**	12446	+2
.1006	12301	0	**.118**	12898	+3	**.139**	09340	0	**.650**	11362	+3
.1007	12300	0	**.119**	12533	+2	**.140**	11217	+4	**.700**	12004	0
.1008	14117	+2	**.120**	12219	0	**.141**	13363	+2	**.750**	14395	+3
.1009	06342	+4	**.121**	12813	+1	**.142**	12100	+1	**.800**	14520	0
.101	09140	0	**.122**	08282	0	**.143**	08524	0	**.850**	14819	+1
.102	12815	-2	**.123**	12736	+2	**.144**	09759	+3	**.900**	14557	-2
.103	12747	+2	**.124**	12170	+1	**.145**	09052	0	**.950**	14010	+3
.104	12147	0	**.125**	14475	+2	**.146**	14779	+1	**1.000**	14330	+3
.105	12913	+4	**.126**	12708	-1	**.147**	12271	+3	**2.000**	12005	+5
.106	11484	+4	**.127**	14885	+2	**.148**	14935	-1	**3.000**	12252	-4
.107	11278	+4	**.128**	13273	+3	**.149**	12244	+1	**4.000**	12932	+6
.108	11195	+1	**.129**	14225	+3	**.150**	12403	+4			
.109	14259	+1	**.130**	14638	+3	**.200**	11634	+4			
.110	13408	+3	**.131**	08004	+2	**.250**	14108	+2			

Figure Shown is deviation from Marked Size of Block in millionths of an inch.
All measurement are based on the international inch(1.00inch=25.4mm)and were made at a measuring temperature of 68 F(20℃).
The gage blocks are made to meet stability requirements of ASME B89.1.9-2002.

Quality Assurance:

- For a set of gauge blocks–metal blocks used as references in a machine shop.
- Traceable to standards at the National Institute of Standards and Technology (NIST).
- Specified deviations from the length standard are given in millionths of an inch.

Another Way to Establish a Standard for Mass

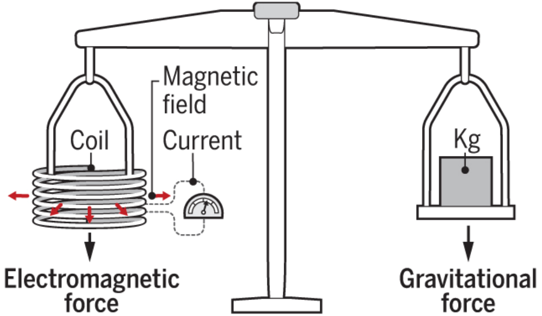


Illustration from Cho, A. (2017). *Science*, 356, 670–671.
http://dx.doi.org/10.1126/science.356.6339.670

- One of the ways used to redefine the kg in 2019, by reference to a defined physical constant, Planck's constant.

- Kibble balance, or "moving coil Watt balance"
- Electric current in coil, within a magnetic field, generates a force opposite to gravitational force on the other side.
- Current is adjusted to match the gravitational force of the unknown mass.
- Many electronic balances, or "scales" operate by same basic principle.
- Key is internal calibration of coil and magnet.

Basic Dimensions in the Current Metric System

International System of Units (SI)

Dimension	Symbol	SI Unit
Length	L	meter (m)
Mass	M	kilogram (kg)
Time	t	second (s)
Thermodynamic temperature	T	kelvin (K)
Electric current	I	ampere (A)
Amount of substance	?	mole (mol)
Luminous intensity	I_v	candela (cd)

- Choice of some of the basic units is somewhat arbitrary.
- Are all of these necessary?

Examples of Derived SI Units

Dimension	Symbol	SI Unit
Area	$A = L^2$	m^2
Volume	$V = L^3$	m^3
Velocity	$v = L/t$	m/s
Acceleration	$a = v/t = L/t^2$	m/s^2
Force	$f = Ma = M \cdot L/t^2$	newton (N) = $kg{\cdot}m/s^2$
Energy	$E = f \cdot L$	joule (J) = Nm = $kg{\cdot}m^2/s^2$

Standard Prefixes for SI Units

prefix	abbreviation	multiplier	examples
nano	n	10^{-9}	nm, ng
micro	μ	10^{-6}	μm, μg
milli	m	10^{-3}	mm, mg
centi	c	10^{-2}	cm, cg
deci	d	10^{-1}	dm, dg
kilo	k	10^{3}	km, kg
mega	M	10^{6}	Mm, Mg

You should know these!

Using Units in Calculations

- Dimensional analysis:
  Treat dimensions and units as symbols that can be manipulated by standard rules of algebra.
- Conversion factors:
  - As a rule: "To convert from kilometers to meters, multiply by 1,000."
  - As an equation: $1\,\text{km} = 1,000\,\text{m}$

Clicker Question #4

Which of these equations does *not* make sense:

A) $1\,\text{mg} = 1\,\text{g}/1,000$

B) $1\,\text{mile} = 1.609344\,\text{km}$

C) $\boxed{1\,\text{kg} = 1\,\text{liter}}$

D) $1\,\text{meter}/\text{s} = 1,1969\,\text{feet}/\text{hour}$

- To make sense, the **dimensions** on the two sides of the equations have to be consistent.

  The **units** do not have to be the same or be part of the same system.

Why isn't "$1\,\text{kg} = 1\,\text{liter}$" a Valid Equation?

- A true statement:
  1 L of water has a mass of 1 kg (within about 0.01 g at 4°C).
- Another (equivalent) true statement:
  The density of water, d_w, has a value of approximately 1 kg/L, or:

$$d_w = 1\,\text{kg}/\text{L}$$

- A valid equation to calculate the mass of a given volume of liquid:

$$\begin{aligned} \text{mass} &= \text{volume} \times \text{density} \\ &= 1\,\text{L} \times 1\,\text{kg}/\text{L} = 1\,\text{kg} \end{aligned}$$

- In mathematics, equality has a very specific meaning: Two things, after evaluation, are completely interchangeable.
- Mass and volume are not the same thing!

Algebraic Rearrangement of a Conversion Factor

$$1\,\text{km} = 1,000\,\text{m}$$

$$\frac{1\,\text{km}}{1,000\,\text{m}} = 1$$

$$\frac{1,000\,\text{m}}{1\,\text{km}} = 1$$

$$1\,\text{m} = 0.001\,\text{km}$$

- All of these equations are valid and equivalent.
- Any quantity can be multiplied (or divided) by 1 to give the same value.

Conversion by Multiplication

- Convert 37 miles to kilometers

$$1\,\text{mi} = 1.609344\,\text{km}$$
$$1.609344\,\text{km}/\text{mi} = 1$$

$$\begin{aligned} 37\,\text{mi} \times 1.609344\,\text{km}/\text{mi} &= 59.6\,\text{mi}\cdot\text{km}/\text{mi} \\ &= 59.6\,\text{km} \end{aligned}$$

- What if we divide instead of multiply?

$$37\,\text{mi} \div 1.609344\,\text{km}/\text{mi} = 23\,\text{mi}^2/\text{km}$$

This is correct algebraically, but it doesn't make much sense physically!

Clicker Question #5

"English" units for mass:

- 1 lb = 16 oz (avoirdupois)
- 1 oz = 28.349523125 g
- 1 stone = 14 Lb

If someone weighs 11 stone, what is that person's mass in kg?

A) $\sim$ 50 kg

B) $\sim$ 70 kg

C) $\sim$ 90 kg

D) $\sim$ 110 kg

Stones to kg

$$11\,\text{stone} \times 14\,\text{lb/stone} = 154\,\text{lb}$$

$$154\,\text{lb} \times 16\,\text{oz/lb} = 2.46 \times 10^3\,\text{oz}$$

$$2.46 \times 10^3\,\text{oz} \times 28.35\,\text{g/oz} = 6.98 \times 10^4\,\text{g}$$

$$6.98 \times 10^4\,\text{g} \div 1000\,\text{g/kg} \approx 70\,\text{kg}$$

$$1\,\text{kg} \approx 2.2\,\text{lb}$$

Clicker Question #6

How many hydrogen ions (H^+) are in a typical bacterium?

A) 1

B) 100

C) 1 thousand

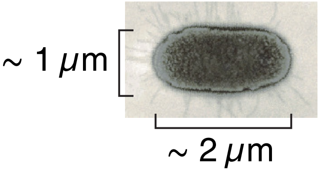
D) 1 million (10^6)

E) 1 billion (10^9)

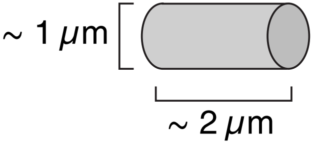
All answers count (for now)!

Scale and Dimensions of a Bacterial Cell

- A typical bacterium found in the human gut: *Escherichia coli*



- Approximate this as a cylinder



- Volume of cylinder = $L \times A$

  L = length of cylinder

  A = area of cap = $\pi \times R^2$

Volume of Cylinder Representing a Bacterium

- Using units of μm:

$$\begin{aligned} V = L \times A &= L \times \pi \times R^2 \\ &= 2\,\mu\text{m} \times \pi \times (0.5\,\mu\text{m})^2 \\ &= 1.6\,\mu\text{m}^3 \end{aligned}$$

- Convert to m^3

$$1\,\mu\text{m} = 10^{-6}\,\text{m}$$

$$1.6\,\mu\text{m}^3 \times \left(10^{-6}\,\text{m}/\mu\text{m}\right)^3 = 1.6 \times 10^{-18}\,\text{m}^3$$

- What about liters or milliliters?

From Cubic Meters to Liters

- An easy-to-remember factoid: $1\,\text{cm}^3$ ("cc") $= 1\,\text{mL} = 10^{-3}\,\text{L}$
- And, $1\,\text{cm} = 10^{-2}\,\text{m}$

$$1\,\text{cm}^3 \times \left(10^{-2}\,\text{m}/\text{cm}\right)^3 = 10^{-6}\,\text{m}^3$$

$$1\,\text{mL} = 10^{-6}\,\text{m}^3$$

$$1\,\text{L} = 10^3\,\text{mL} \times 10^{-6}\,\text{m}^3/\text{mL} = 10^{-3}\,\text{m}^3, \qquad 1\,\text{m}^3 = 10^3\,\text{L}$$

- For our bacterium:

$$1.6 \times 10^{-18}\,\text{m}^3 \times 10^3\,\text{L}/\text{m}^3 = 1.6 \times 10^{-15}\,\text{L}$$

$$1.6 \times 10^{-15}\,\text{L} \times 10^3\,\text{mL}/\text{L} = 1.6 \times 10^{-12}\,\text{mL}$$

- How many bacteria would fit into $1\,\text{mL}$? In one $1\,\mu\text{L}$?