Quantification across scales

class – 3 (8.8.24)

LS2103 (Autumn 2024)

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Details of LS2103 (Autumn 2024)

Level: **2** Type: **Theory** Credits: **3.0**

Course Code	Course Name	Instructor(s)
LS2103	**Biophysics**	**Neelanjana Sengupta**

Syllabus

- Heat as a form of energy: Concept of free energy; free energy transduction; order/disorder in biology; forces and energies
- Molecular interactions: Physical basis and implications in biology
- Dimensions and Units: Dimensional analysis; biomolecules dimensions, arrangements, internal energies
- Special properties of water: Importance in biology
- Overview of structures inside cells: Dimensions, crowding, basic functioning principles, timescales of cellular processes; energies/forces inside live cells. Modes of information transfer;
- Distributions in nature: Origin, implications

Course modules:

I. Introduction: What is Biophysics?

II. Quantification in Biology:

- Time and Length scales; Dimensional analysis
- Avogadro's Number; pH; concentrations

III. Distributions:

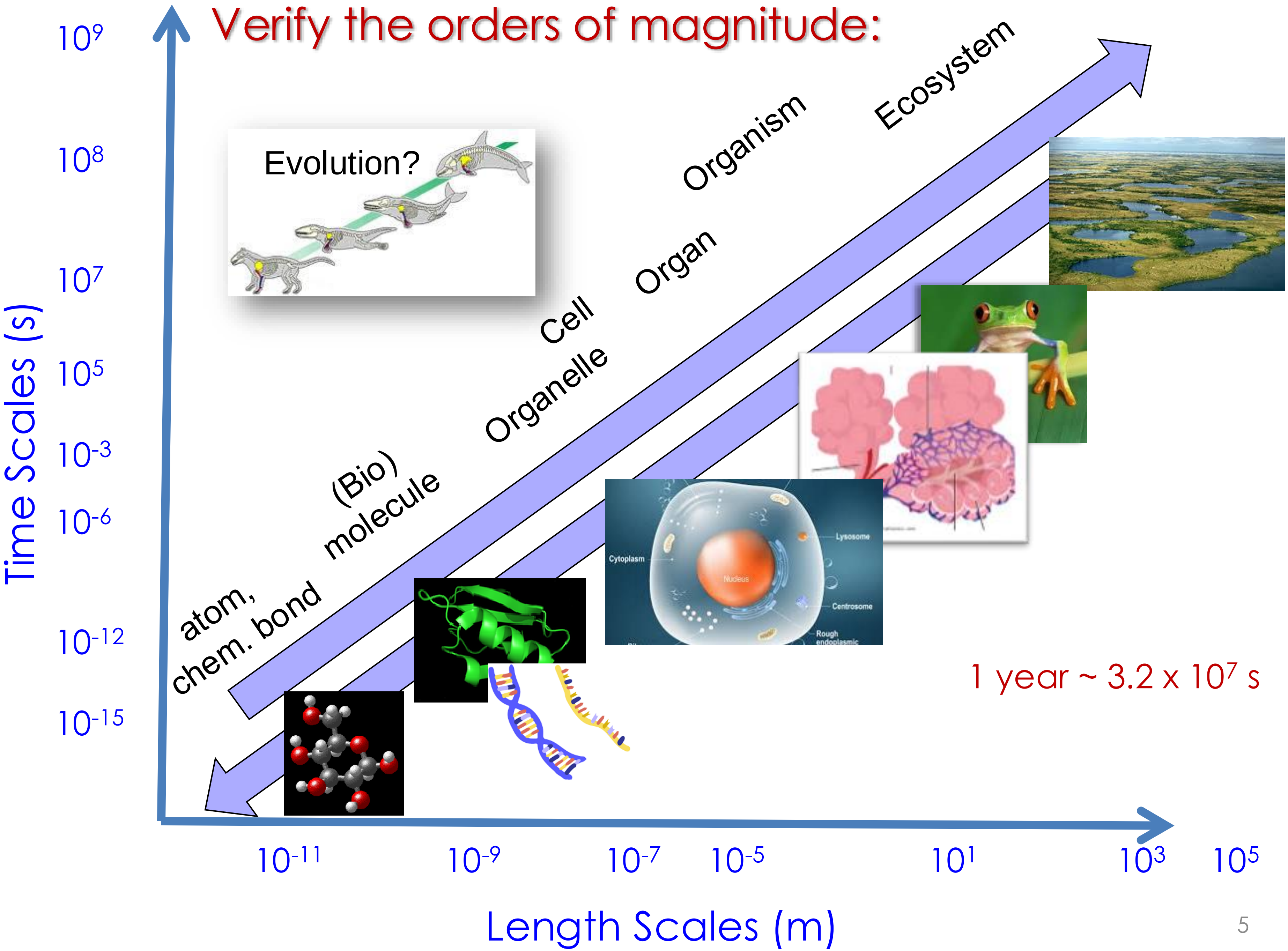
- Thermal motion and velocity distribution
- Normal distributions, deviations
- Ideal Gas Laws; Equilibrium; Boltzmann distribution
- Equipartition; role of $k_B T$ in biology
- Entropy in Biology
- Free Energy, Activation, Scaling Barriers

Course modules:

IV. Connecting the Microscopic and Macroscopic Pictures

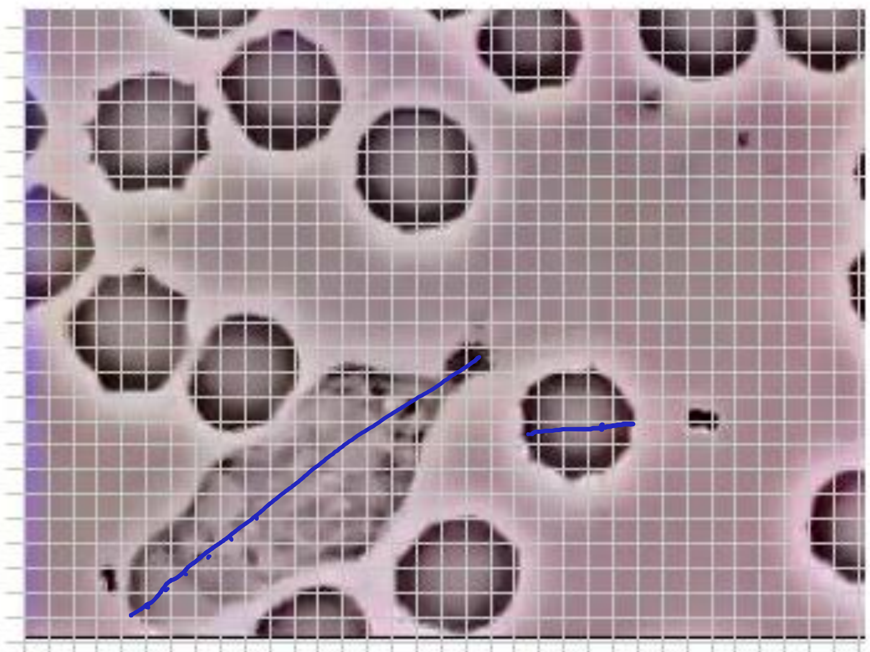
- Brownian Motion
- Diffusion(*) and Dissipation
- Reynold’s number
- Osmotic machine
- Hydrophobicity
- Depletion forces

Verify the orders of magnitude:



Neutrophil chasing bacteria

Red blood cell ~8 μm



What are the approx. sizes of:

a) the neutrophil?

b) the bacteria it is chasing?

c) If the movie was in "real time", what would be the average speed of the bacterium? Does that match with the neutrophil's speed?

‘Rule of Thumb’: Length Scales

Table 1.1: Rules of thumb for biological estimates.

	Quantity of interest	Symbol	Rule of thumb
E. coli			
	Cell volume	$V_{E.\,coli}$	$\approx 1\ \mu m^3$
	Cell mass	$m_{E.\,coli}$	≈ 1 pg
	Cell cycle time	$t_{E.\,coli}$	≈ 3000 s
	Cell surface area	$A_{E.\,coli}$	$\approx 6\ \mu m^2$
	Macromolecule concentration in cytoplasm	$c_{E.\,coli}^{macromol}$	≈ 300 mg/mL
	Genome length	$N_{bp}^{E.\,coli}$	$\approx 5 \times 10^6$ bp
	Swimming speed	$v_{E.\,coli}$	$\approx 20\ \mu m/s$
Yeast			
	Volume of cell	V_{yeast}	$\approx 60\ \mu m^3$
	Mass of cell	m_{yeast}	≈ 60 pg
	Diameter of cell	d_{yeast}	$\approx 5\ \mu m$
	Cell cycle time	t_{yeast}	≈ 200 min
	Genome length	N_{bp}^{yeast}	$\approx 10^7$ bp
Organelles			
	Diameter of nucleus	$d_{nucleus}$	$\approx 5\ \mu m$
	Length of mitochondrion	l_{mito}	$\approx 2\ \mu m$
	Diameter of transport vesicles	$d_{vesicle}$	≈ 50 nm

Phys. Bio. of Cell., Garland Science, Ch. 1

‘Rule of Thumb’: Length Scales

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	Macromolecule concentration in cytoplasm	$c_{E.\,coli}^{macromol}$	≈ 300 mg/mL
	Genome length	$N_{bp}^{E.\,coli}$	$\approx 5 \times 10^6$ bp
	Swimming speed	$v_{E.\,coli}$	$\approx 20\ \mu m/s$

I. What is the “**surface-to-volume**” ratio of *E. coli*?
- Unit?
- How is this expected to scale with size of organism?

II. What is the average cell cycle duration of *E. coli* in days?

III. Approx. how many times it’s ‘body size’ does *E. coli* cover per second?
- How would you compare this movement with that of a fastest humans?
  (Usain Bolt’s speed ~12.4 m/s, ie. ~10 x 1.2 m/s)

‘Rule of Thumb’: Length Scales

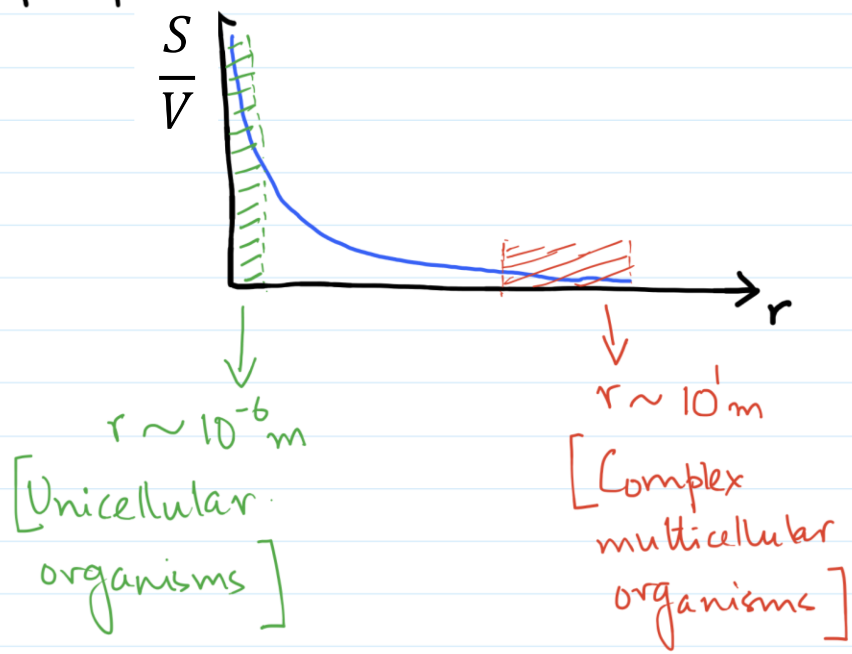
I. Construct a model for the “**surface-to-volume**” ratio of *E. coli*

'Rule of Thumb': Length Scales

Surface-to-Volume ratios of organisms (in general)

In general, for any entity of spatial scale 'r',

$$\frac{S}{V} \propto \frac{1}{r}$$

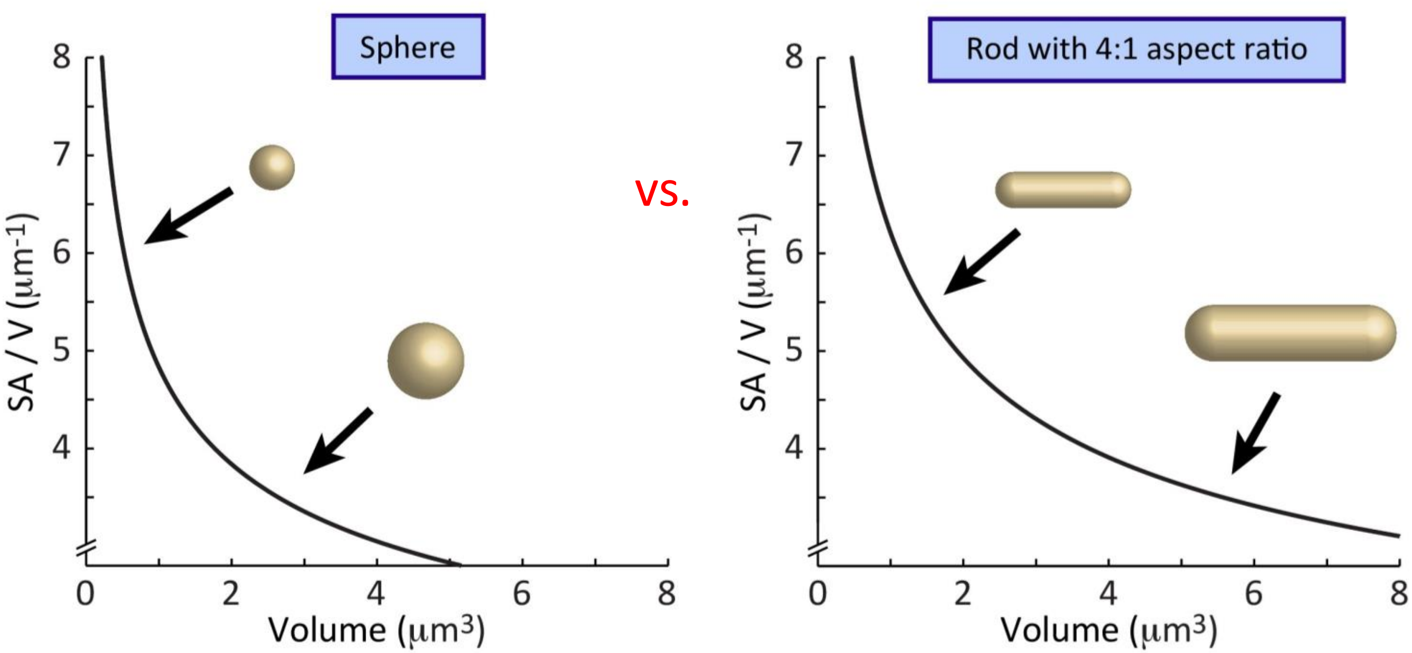


- The (S/A) ratio is high for prokaryotes
- It reduces in complex multicellular organisms
  - *It is not very sensitive to size in multi-cellular organisms*

Bacteria: Surface to Volume (S/V) ratio

- Within a species, size can be variable
- But (S/V) generally maintained if the conditions do not change
- What triggers bacteria shape and size changes?

(B) Hold shape constant



Trends in Microbiology 2018, 26815-832 , DOI: (10.1016/j.tim.2018.04.008)

‘Rule of Thumb’: Length Scales

Table 1.1: Rules of thumb for biological estimates.

	Quantity of interest	Symbol	Rule of thumb
Water			
	Volume of molecule	V_{H_2O}	$\approx 10^{-2}$ nm^3
	Density of water	ρ	1 g/cm^3
	Viscosity of water	η	$\approx$1 centipoise (10^{-2} g/(cm s))
	Hydrophobic embedding energy	$\approx E_{hydr}$	2500 cal/(mol nm^2)

- What is the approx. radius of water molecule?
- What is the ”E_{hydr}” given above?

'Rule of Thumb': Length Scales

Table 1.1: Rules of thumb for biological estimates.

Quantity of interest	Symbol	Rule of thumb
Amino acids and proteins		
Radius of "average" protein	$r_{protein}$	≈ 2 nm
Volume of "average" protein	$V_{protein}$	≈ 25 nm^3
Mass of "average" amino acid	M_{aa}	≈ 100 Da
Mass of "average" protein	$M_{protein}$	$\approx 30{,}000$ Da
Protein concentration in cytoplasm	$c_{protein}$	≈ 150 mg/mL
Characteristic force of protein motor	F_{motor}	≈ 5 pN
Characteristic speed of protein motor	v_{motor}	≈ 200 nm/s
Diffusion constant of "average" protein in cytoplasm	$D_{protein}$	$\approx 10\ \mu$m^2/s

- How does mass of a typical amino acid, and a typical protein, compare with mass of a water molecule?

'Rule of Thumb': Length Scales

Table 1.1: Rules of thumb for biological estimates.

Quantity of interest	Symbol	Rule of thumb
Lipid bilayers		
Thickness of lipid bilayer	d	≈ 5 nm
Area per molecule	A_{lipid}	$\approx \frac{1}{2}$ nm^2
Mass of lipid molecule	m_{lipid}	≈ 800 Da

- Consider that a protein of radius 1 nm displaces water to embed into a lipid bilayer.
- Estimate the energetic cost in kcal/mol.

Quantity of interest	Symbol	Rule of thumb
DNA		
Length per base pair	l_{bp}	$\approx 1/3$ nm
Volume per base pair	V_{bp}	≈ 1 nm^3
Charge density	λ_{DNA}	$2\,e/0.34$ nm
Persistence length	ξ_p	50 nm