LECTURE 3

BB 101

MODULE: *PHYSICAL BIOLOGY*

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Review of Lecture 2

- How surrounding medium affects functioning of biological systems?
- Critical Viscous Force and Reynolds number
- Life at low Reynolds number
- A low-Reynolds number microorganism can't swim by executing ***geometrically reciprocal motion***
- Swimming of microorganism
- Swimming by reciprocal motion in non-Newtonian fluid

So far.....

We looked at the **forces** at molecular and cellular scales

Cellular world is predominately governed by **viscous forces**

As a consequence, **inertial forces** can be safely ignored in most cases

What about energies?

Thermal Energy and Thermal Forces

- Proteins and cells are subjected to thermal forces, arises due from **collision** of water and other molecules in their surrounding fluid

- These collision forces are called **thermal forces** because their magnitude is proportional to temperature of the fluid molecules.

Thermal Motion and Thermal Energy

- The resulting movement of object is called **thermal motion**, and object is said to have **thermal energy**
- Since **thermal forces** are randomly directed, the resulting thermal motion is characterized by frequent changes in direction and is called **diffusion**
- Diffusion of a free particle or object is called **Brownian motion**

Brownian Motion

Figure Source:
http://www.nndb.com/people/050/000100747/

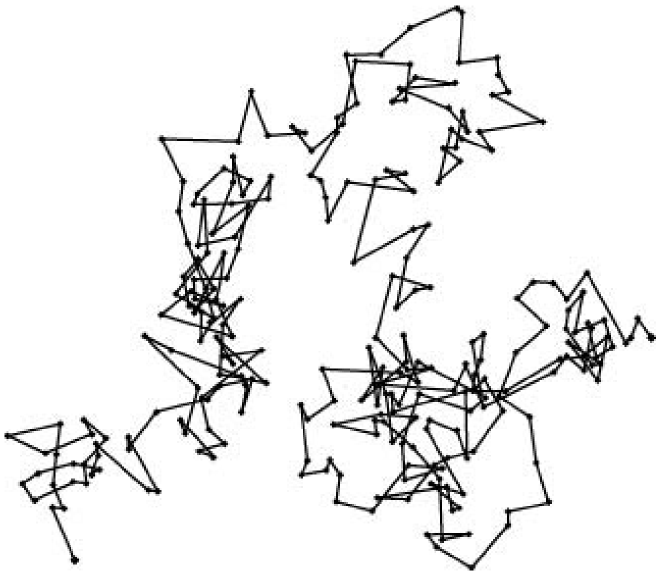


Figure Source: http://www.doc.ic.ac.uk/~nd/surprise_95/journal/vol4/ykl/report.html

In 1828, botanist Robert Brown noticed that pollen grains suspended in water dance in zig-zag manner

- Initially thought that it was signature of life
- Careful observer and proceeded to check his assumption
- Repeated observations with many lifeless particles, and all of them showed the same (suspension of coal dust, pulverized stone etc.)

Watch Video of Brownian Motion of pollens in water
https://www.youtube.com/watch?v=R5t-oA796to

Thermal Energy

- We saw that objects suspended in fluid can gain thermal energy and this thermal energy can make them to dance

- The thermal energy at temperature T is given by $k_B T$, where k_B is Boltzmann constant

- Thermal energy at room temperature

$$\mathbf{k_B T = 4.1 pN\ nm}$$

Is this thermal energy important in biology ?

Relative Importance of Thermal Energy

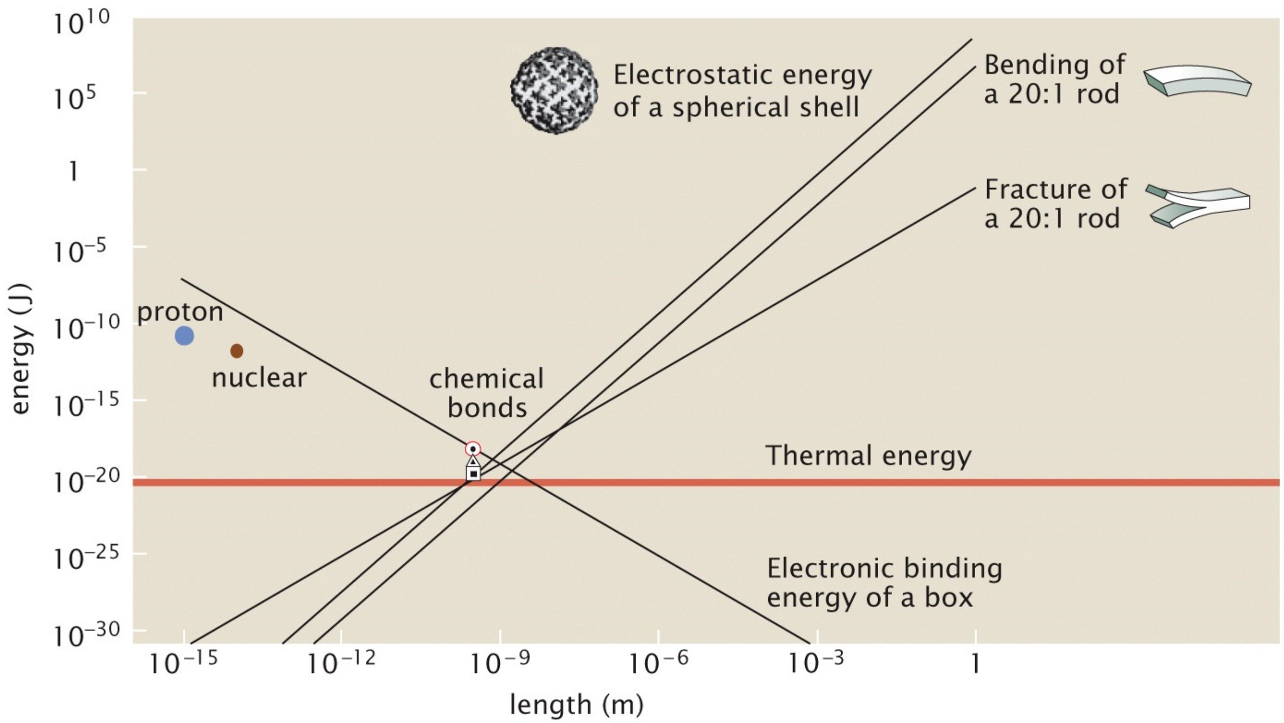


Figure 5.1 Physical Biology of the Cell, 2ed. (© Garland Science 2013)

The electrostatic energy is estimated for a model spherical protein with polar residues on its surface and for which all of the polar residues are stripped of a single charge

Chemical energy as a function of length, or binding energy, is estimated approximately by considering the effects of confining a free electron in a box of that length scale.

Relative Importance of Thermal Energy

- At the scale of macromolecule of the cells (nm) deterministic energies of bonding, charge rearrangement and molecular rearrangement are comparable

- Because each of these forms of energy is of comparable scale and effectively interchangeable at the molecular level, a living organism that needs to generate motion, heat, electricity, and biomolecular synthesis is expert at energetic interconversions.

Thermal Energy and Biological Systems

It becomes important to consider thermal energy at macromolecular scales

Thermal energy can be safely ignored at macroscopic level.

It turn out that state of a biological system at molecular scale is decided by the competition between deterministic energy and thermal energy

Boltzmann's Law

Fundamental physical law that describes how probability of finding a molecule in a certain state depends on the energy of that state and surrounding temperature

A particle or molecule always tends to remain in its lowest energy state

At non-zero temperature, due to molecular collisions, they can spend their time in higher energy states

Boltzmann's Law

Boltzmann's law says that if such a particle is in thermal equilibrium, then the probability p_i of finding the particle in state i that has energy U_i is given by

$$\boxed{p_i = \frac{1}{Z} e^{-\frac{U_i}{k_B T}}}$$

Where $z = \sum_i e^{-\frac{U_i}{k_B T}}$ is called partition function

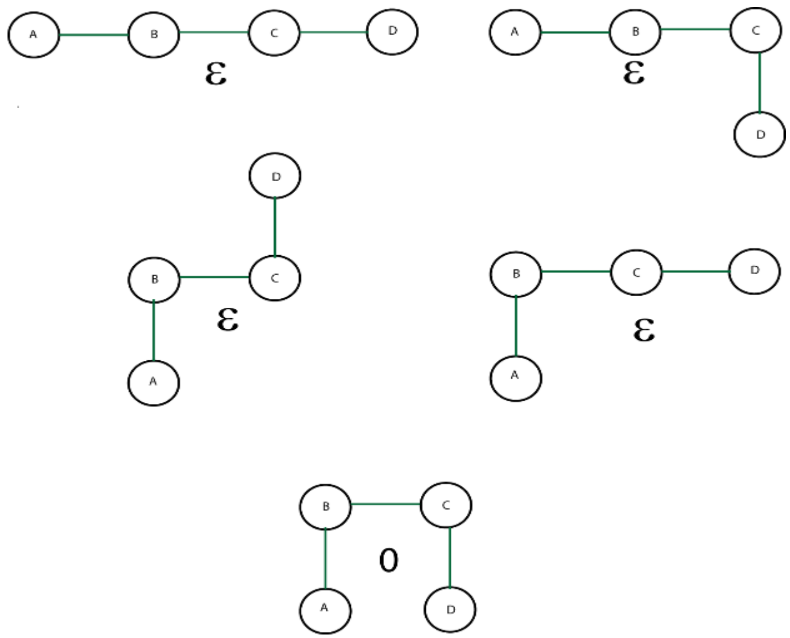
The exponential term is called Boltzmann factor

Partition function tells you how the system will be partitioned or divided into different possible states

Partition Function

Consider a chain of four distinguishable amino acids with energy ϵ. This chain can switch between open conformation(s) or closed conformation(s) in a plane due to change of bond angles by 90^0 due to thermal fluctuations. Assume that energy of this system is not changed due to change of bond angles. However, if the distance two un-bonded amino acids due to change of bond angles become equal to bond length, then energy of the chain reduces by ϵ. Find out the partition function (Z) for this system T=0 and T=∞?

Partition Function



Boltzmann's Law: Some comments

Boltzmann's law is very general. The energy could correspond to particle's potential energy (gravitational, elastic or electrical), its kinetic energy or the energy associated with its phase, or electronic or chemical state

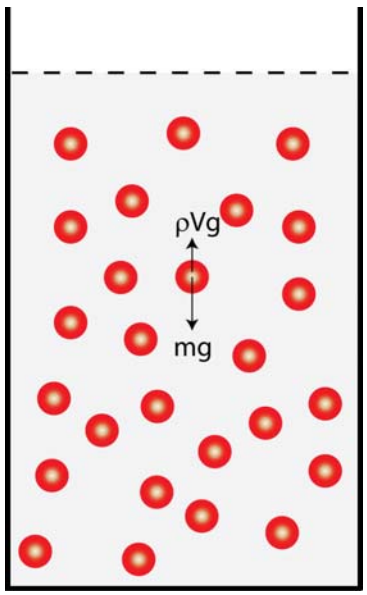
If there are just two states with energies U_1 and U_1 (and energy difference $\Delta U = U_2 - U_1$) then

$$\boxed{\frac{p_2}{p_1} = e^{-\frac{\Delta U}{k_B T}}}$$

Applications of Boltzmann's Law

Equilibrium Colloidal Suspension or Colloids

Macromolecules and many other soluble proteins form colloidal suspensions in water



colloidal suspension of globular proteins

Sedimentation Equilibrium in Gravity

Gravity: mg　　　　Buoyant Force: ρVg

Net gravitational force: $(m-\rho V)g \equiv m_{net}g$

Profile of particle density is given by

$$\boxed{\frac{C_h}{C_0} = e^{-\frac{m_{net}gh}{k_BT}} = e^{-\frac{h}{h^*}}}$$

Competition between gravitational and thermal energy

For myoglobin protein

$$m_{net} = 17000\frac{g}{mole}$$

$$\Rightarrow h_* = \frac{k_BT}{m_{net}g} \approx 60m$$

In a 4 cm test tube $\frac{C_h}{C_0} = e^{-\frac{0.04}{60}} = 0.999 = 99.9\%$

Probability of finding particle at height h and the bottom are roughly same

Colloidal suspension will never sediment

Applications of Boltzmann's Law

Nernst Equation

Most spectacular application of biological electricity by cells is the action potential in the nerve cells

This is used to rapidly propagate information from the nerve cell body to the tip of axon

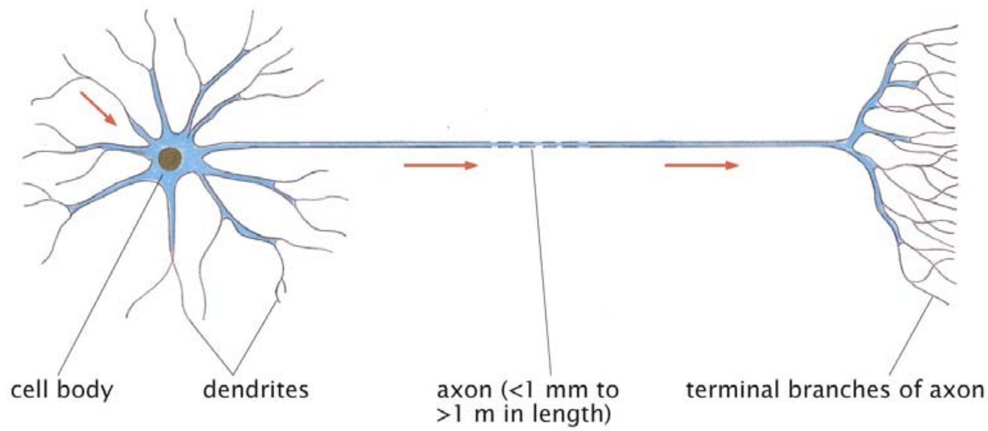


Figure 17.1 Physical Biology of the Cell, 2ed. (© Garland Science 2013)

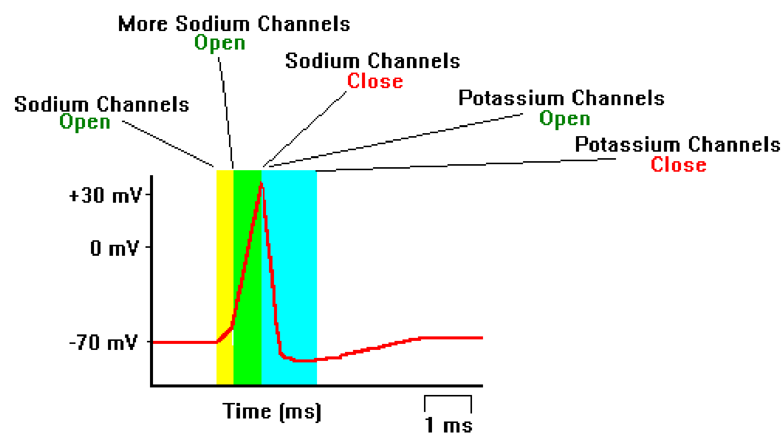
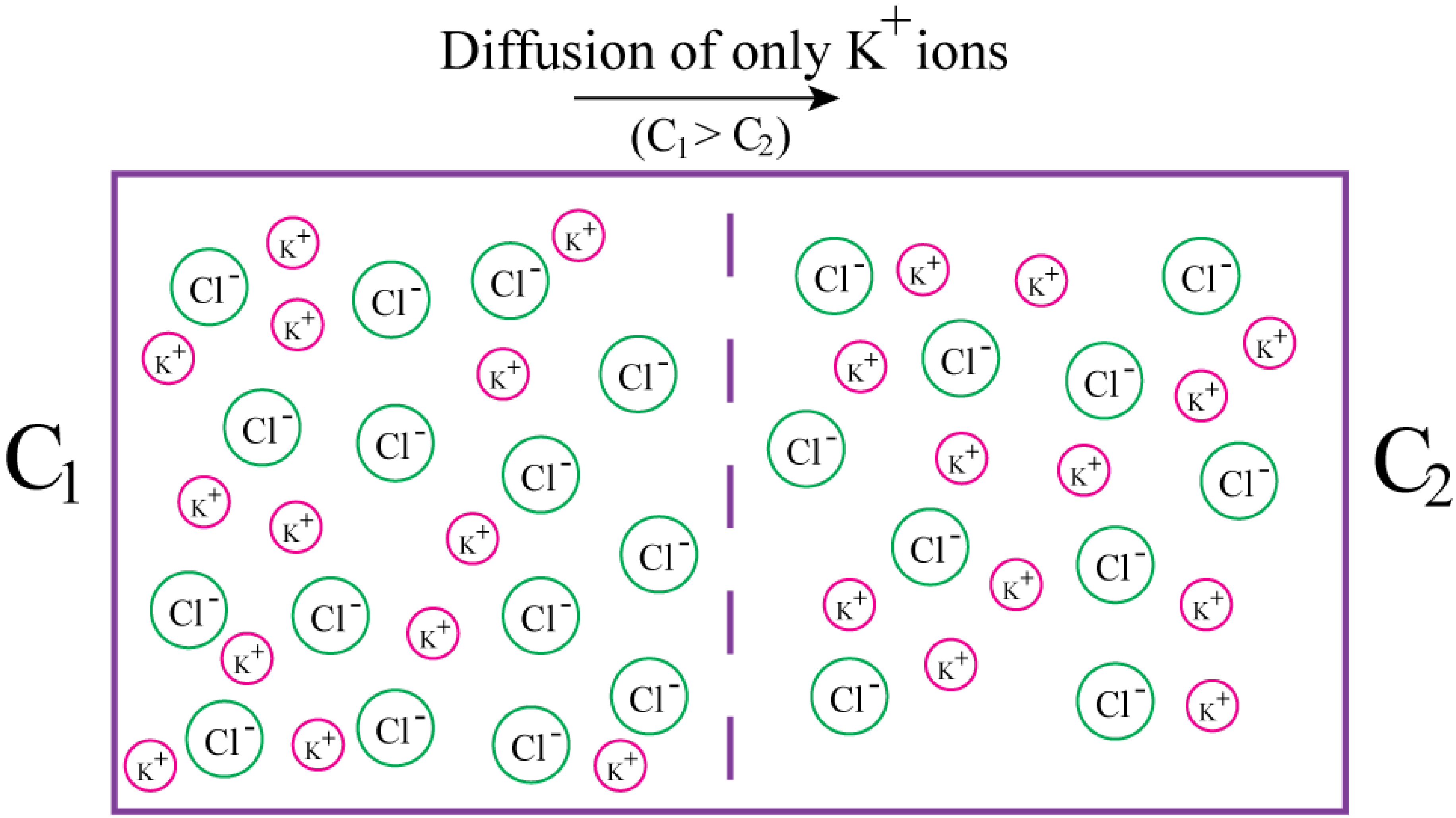


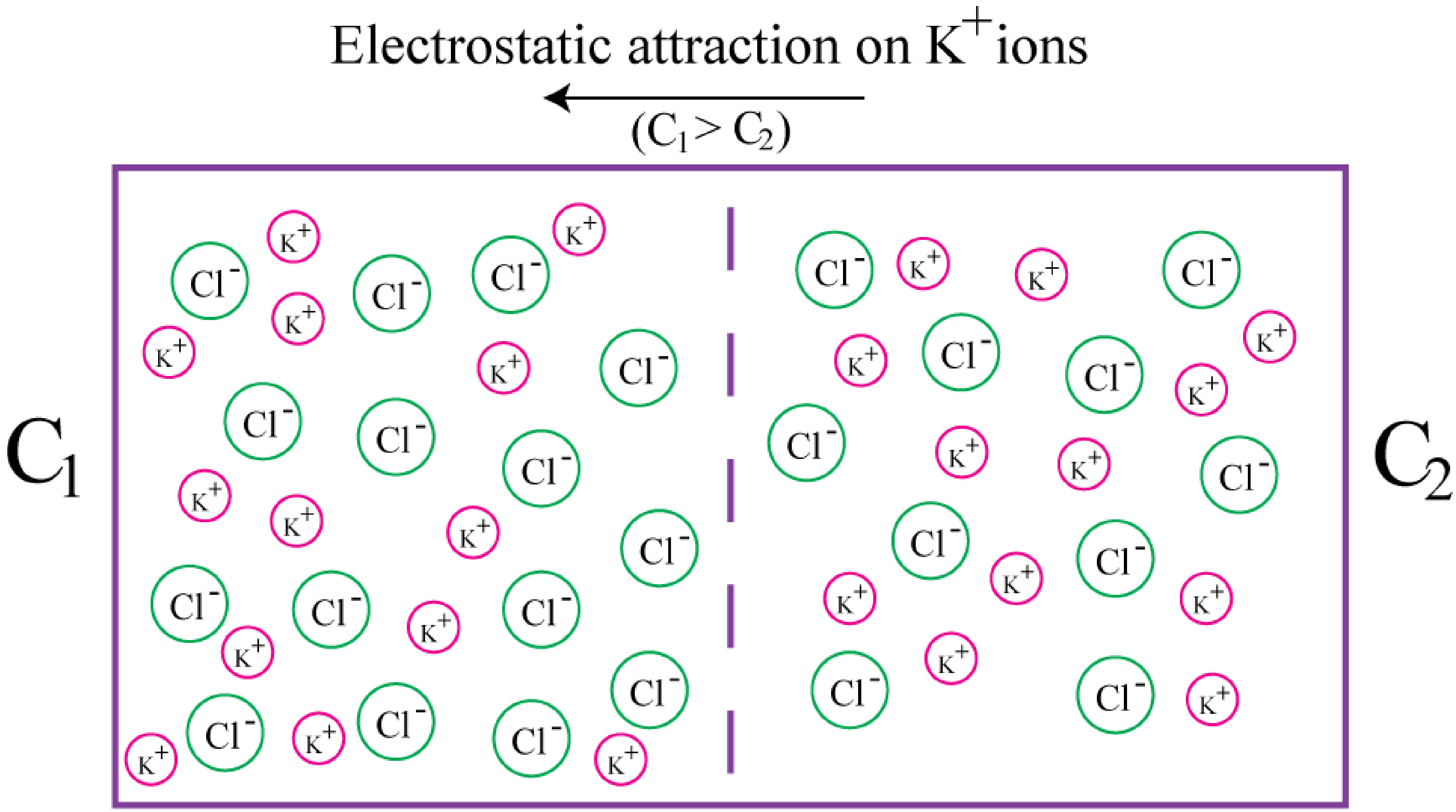
Figure Source: https://faculty.washington.edu/chudler/ap.html

Ion concentration difference across membrane lead to potential difference

Nernst Equation



Nernst Equation



Nernst Equation

$$\frac{p_1}{p_2} = \frac{C_1}{C_2} = \frac{e^{-\frac{zeV_1}{k_B T}}}{e^{-\frac{zeV_2}{k_B T}}}$$

$$V_2 - V_1 = \frac{k_B T}{ze} ln \frac{C_1}{C_2}$$

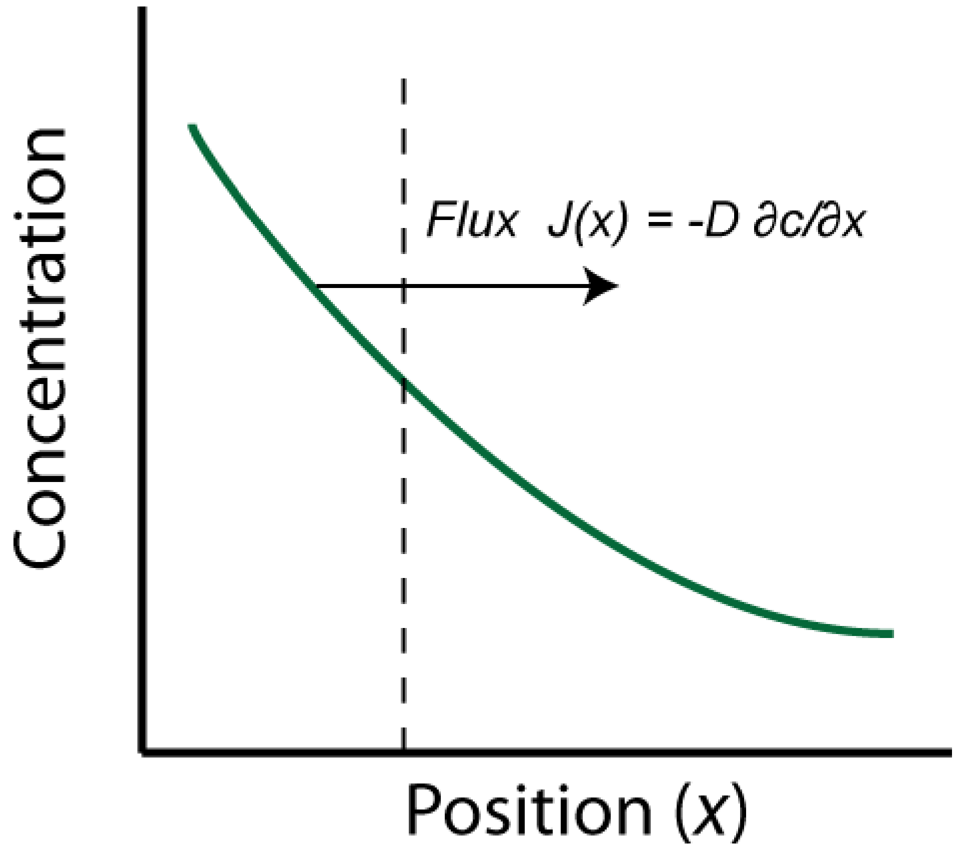
Ion species	Intracellular concentration (mM)	Extracellular concentration (mM)	Nernst potential (mV)
K^+	155	4	−98
Na^+	12	145	67
Ca^{2+}	10^{-4}	1.5	130
Cl^-	4	120	−90

Diffusion Equation

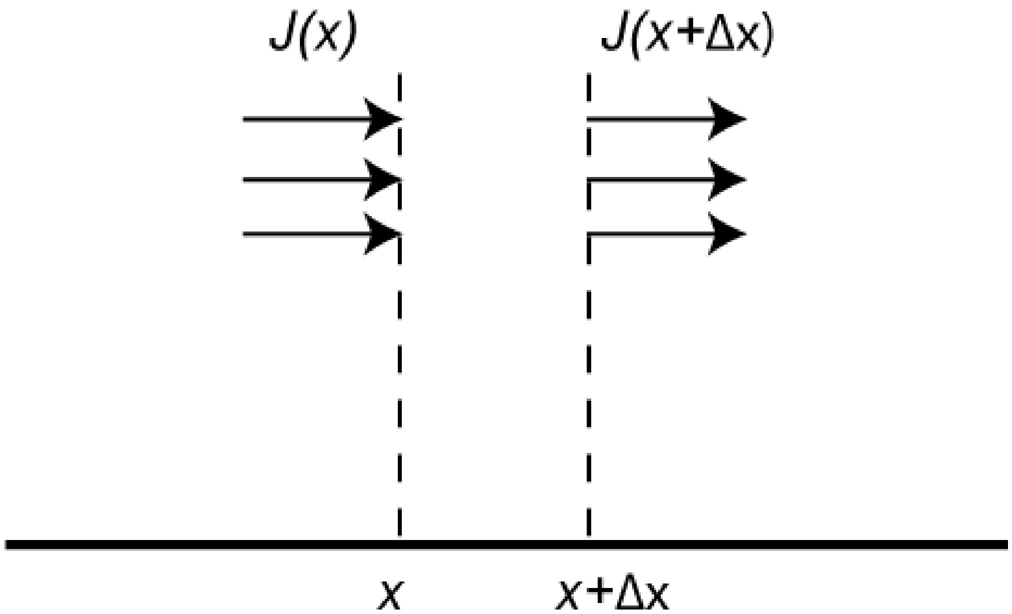
- Links change of concentration in time to change of concentration in space

- Combining Fick's law and continuity equation

Fick's Law



Continuity Equation



If inflow=outflow then concentration at x doesn't change with time

However, if inflow ≠ outflow then concentration at x will change with time

Summary

- Boltzmann’s law
- Applications of Boltzmann’s law
- Fick’s law
- Continuity Equation
- Diffusion Equation