DIFFUSION

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Experiment: add a droplet of ink to water containing glass container. What does happen?

Observation?
The stain (ink) spreads and eventually colours the entire water.

The materials will eventually be dispersed in their gas or liquid space. This process name is DIFFUSION.
EVERYDAY EXAMPLES OF DIFFUSION

Biological importance of diffusion:

• transport through the cell membrane (membrane transport)
• metabolism (gas exchange between blood and lungs)
• stimuli
• absorption of medicines
• chemical reactions
• (inter- or intracellular molecular movements)
Why does the particles spread in the water? Why does this process is faster at higher temperature than at lower temperature?

If we want to understand these processes, we have to search the answer in microscopic/molecular processes.
Motion of particles
Most of the particles of biological system are in constant motion.

in fluid phase – aqueous medium (55-60% human body consist of water)
in lipid phase – cell membrane (exhibit higher order organisation)

Brownian motion
Robert Brown (scottish botanist, 1827)
experiment: microscopic investigation of pollen in water
observation: random, zig-zag motion of pollen particles,
similar to gas particles

explanation?
Brownian motion – basis of the diffusion

The motion of the particles are random (a series of inflexible collisions)
As a consequence of the repeated collisions with surrounding particles (continuous collision between the particle)
Depends on the temperature (T): thermal motion

Kinetic energy $= \frac{1}{2} m \bar{v}^2 = \frac{3}{2} kT \sim \text{temperature}$ (thermal motion)
Essentials of diffusion

- The diffusion is the consequences of a non uniform (inhomogeneous) distribution of the particles

- **What does happen during diffusion?**

  a particles directional movement * from the regions of higher concentration → to regions of lower concentration, which continues until the distribution of the particles is uniform (homogeneous)

* Brownian motion inhomogeneous homogeneous
What does the diffusion depends on?
Quantitative description of diffusion

**Fick’s first. law – quantifying diffusion in space**
For simplicity, let’s investigate the diffusion in 1D (along the x axis)

![Diagram showing diffusion in 1D](image)
Description of diffusion with spatial variations in concentration

- the spatial variation of the concentration \( (c) \) along the \( x \) axis is decreasing

- **CONCENTRATION GRADIENT** (driving force): the ratio of the change in the concentration \( (\Delta c) \) and the distance \( (\Delta x) \) between two points

- for simplicity: the concentration changes linearly

\[
\frac{\Delta c}{\Delta x} = \text{constant}
\]
Quantifying diffusion

- **Particle flux:** During (Δt) time, how many particles (ΔN, number of the particles) travels.

\[
I_N = \frac{\Delta N}{\Delta t}
\]

\[
1 \text{ sec}^{-1}
\]

- **Matter flow rate:**

\[
I_V = \frac{\Delta n}{\Delta t}
\]

\[
\Delta n = \frac{\Delta N}{N_A}
\]

\[
\text{mol sec}^{-1}
\]

- **Matter flow density \( \approx \) velocity ("strength") of diffusion

number of moles of substance travelling through a unit surface during a time interval of unity

\[
J_V = \frac{\Delta I_V}{\Delta A} = \frac{\Delta n}{\Delta A \Delta t}
\]

\[
\text{mol m}^{-2} \text{ sec}^{-1}
\]
FICK’S 1ST LAW
(spatial description)

The matter flow density \( J = \frac{\Delta n}{A \Delta t} \) is linearly proportional with the gradient of concentration \( -\frac{\Delta c}{\Delta x} \).

\[
J = -D \frac{\Delta c}{\Delta x}
\]

Difference of concentration/ diffusion↑ → velocity of diffusion↑

What is the reason of negative sign?

The particles diffuse from the region of higher concentration to the region of lower concentration.

D = /diffusion coefficient/: it determines the properties of particles and medium
Diffusion coefficient (D)

- symbol: $D$
- unit: $\frac{m^2}{sec}$
- characterises the mobility of a diffusing particle → tell us how 'fast' a given substance diffuses
- gives the amount of substance ($\Delta n$) that diffuses through a surface ($\Delta A$) unit during a time, if the concentration drop was unity
- depends on both the diffusing particle and the medium in which the particle diffuse
Diffusion coefficient ($D$) - Einstein-Stokes equation

Diffusion of a spherical particles ($r$:radius) in a viscous medium ($\eta$) at $T$ temperature:

$$D = \frac{kT}{6\pi\eta R}$$

- **temperature ($T$)**
  
  the diffusion is faster at higher temperature: faster thermal motion

- **geometry/shape of the particles ($r$)**
  
  small/globular particles diffuse more easily than big/fibrillar particles

- **molecular weight of the particle($M$)**
  
  heavier particles diffuse more slowly than the lighter ones

- **viscosity of the medium ($\eta$)**
  
  diffusion is faster in low viscosity media, than in the higher viscosity media, e.g: gases > liquids

**k:** Boltzmann constant $k = 1.38 \times 10^{-23}$ joule/kelvin
FICK’S 1ST LAW – **spatial description**

- concentration difference (driving force)
- diffusion (matter flow)
- homogeneous distribution (equilibrium)

we quantified the diffusion considering the spatial variations \( c(x) \) in concentration.

FICK’S 2ST LAW – **spatial and temporal description**

... but we have not considered that the concentration changes with time, too \( c(x, t) \)!

What else? – something is missing...
Quantifying diffusion in spatial and temporal (FICK’S 2\textsuperscript{ST} LAW) for simplicity: we still examine in the one-dimensional situation:

\[ \frac{\Delta c}{\Delta t} = D \left( \frac{\Delta (\frac{\Delta c}{\Delta x})}{\Delta x} \right) \]

The change in concentration (\( \frac{\Delta c}{\Delta t} \)) over time at a given place is linearly proportional with the changing of concentration gradient (\( \frac{\Delta c}{\Delta x} \)) at time (\( \frac{\Delta (\frac{\Delta c}{\Delta x})}{\Delta x} \)).

D: diffusion coefficient
How far does the particle get from its initial position during $t$ time? $R(t)=?$

The migration of particle can be described with a distribution function (Gaussian function)

$$\bar{R}(t) \sim \sqrt{2Dt}$$

The average value of $R(t)$ is linearly proportional to the square-root time.
Notice...

The diffusion time \((t)\) is proportional to the square of the diffusion distance \((R)\).

\[
\bar{R} \ (t) \sim \sqrt{t} \\
t \sim (\bar{R} \ (t))^2
\]

Diffusion
- relatively fast (<seconds) \(\rightarrow\) (100 µm) over short distance
- exceptionally slow (<days) \(\rightarrow\) (100 µm) over long distance
Example: Diffusion through the cell membrane

Lipid bilayer membrane and membrane proteins

Extracellular space

Intracellular space (cytoplasm)

Different mechanism: exocytosis and endocytosis

Diffusion through the cell membrane

The classification of the transport processes

I. TRANSPORT MECHANISM

PASSIVE DIFFUSION (without mediator)

FACILITATED DIFFUSION (with mediator)

II. ENERGETIC REQUIREMENTS

PASSIVE transport

ACTIVE transport
Diffusion through the cell membrane

THE CLASSIFICATION OF TRANSPORT PROCESSES

Passive diffusion
Passive transport
Without mediator

- **direction of transport**: ELECTRO-CHEMICAL POTENTIAL GRADIENT
  - chemical potential gradient (concentration)
  - electric potential gradient (charge)

- **rate of diffusion**: Fick’s law

- **mediator**: no

- **energetic requirement**: no

- **examples**:
  - hydrophobic molecules: O₂, N₂
  - small polar molecules: CO₂, water, alcohol, urea, glycerol
Facilitated diffusion

Passive transport

With mediator: ION-CHANNELS

- **direction of transport**: chemical or electro-chemical potential gradient
- **rate of diffusion**: faster than that expected from Fick’s law
- **mediator**: ION-CHANNEL PROTEIN
  - transmembrane proteins
  - closed/open state: no transport/transport
  - regulation:
    → mechanically-gated (mechanical tension, cytoskeleton)
    → voltage-gated (potential difference between the membrane)
    → ligand-gated (ligand binding)
  - selectivity: size and charge of the ions
- **energetic requirements**: no
**FACILITATED DIFFUSION**

Passive transport

With mediator: Carrier proteins

- **direction of transport:** chemical or electro-chemical potential gradient
- **rate of diffusion:** faster than that expected from Fick’s law
- **mediator:** CARRIER PROTEIN (transporter)
  - specifically binds the ions or molecules and promotes their transport processes
- **energetic requirements:** no
Diffusion through the cell membrane

THE CLASSIFICATION OF TRANSPORT PROCESSES

FACILITATED DIFFUSION

ACTIVE transport

With mediator: CARRIER PROTEINS

- **direction of transport**: AGAINST the chemical and electrical gradient! **ENERGY IS REQUIRED!**

- **mediator**: TRANSPORTER
  - uniporter
  - symporter
  - antiporter

- **energetic requirements**: yes
  - ATPase transporter (ATP hydrolysis)
  - photo transporter (light energy)
  - coupled transporter (other transporter)

- **example**: Na\(^+\) - K\(^+\) pump
Overview - the most important things

- The Brownian motion (the particles random thermal motion)
- The diffusion

  a particles directional movement * from the regions of higher concentration → to regions of lower concentration, which continues until the distribution of the particles is uniform (homogeneous)

- FICK’S 1\textsuperscript{ST} LAW (spatial description)

\[
J = -D \frac{\Delta c}{\Delta x}
\]

- Diffusion Coefficient (D)

\[
D = \frac{kT}{6\pi \eta R}
\]

- FICK’S 2\textsuperscript{nd} LAW (spatial & temporal description)

- Diffusion through the cell membrane:
  energetic requirements (passive, active) and transport mechanism (passive and facilitated diffusion)
OSMOSIS

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Osmosis in the kitchen

**Experiment I:**
place a dried leaf of salad into water
What does happen?

**Observation:**
The leaf of salad becomes bigger and looks fresh

**Experiment II:**
Place one egg into the (corn) syrup and another egg into the water
What does happen?

becomes bigger  
shrink
What is the main difference between the „ink” experiment and the „salad/egg” experiments?

https://www.teachitenglish.com/lessons/itjC8i1XKQw/How-temperature-affects-food
Osmosis

1. No wall

FREE DIFFUSION
homogeneous
distribution
(transport of the
smaller and larger
molecules)

2. Solid wall (non-permeable)

NO TRANSPORT

3. Special wall (SEMIPERMEABLE)

RESTRICTED DIFFUSION = OSMOSIS
Smaller molecules reach a uniform distribution

Larger molecules remain in the compartment
3. Special wall (SEMIPERMEABLE)

SEMIPERMEABLE = „works as a special filter”: allows smaller molecules („water”) to pass through the membrane, but not the larger molecules (e.g.: sugar)

Special filters: e.g.: cell membrane, animal skin pellicles

OSMOSIS: unidirectional matter flow, which occurs during diffusion (restricted diffusion)

Criterion: semipermeable wall
concentration difference
Quantification of osmosis

0. First state:
- concentration difference for dissolved substance (e.g. sugar)
- semipermeable membrane: allows the water (solvent) to pass through the membrane, but not the solute

1. Solvent flow:
- the solvent pass through the semipermeable membrane
- The volume of the solvent (water) + solute (sugar) mixture increases (high of the column increases)

2. Pressure:
- Hydrostatic pressure increases ($p = \rho gh$)

3. Osmotic equilibrium
- the increase the high of the column stopped

**OSMOTIC PRESSURE:**
- That pressure, which counteract the osmosis

$$p_h = p_{\text{osmosis}}$$

$$p_{\text{osmosis}} = \rho gh$$
Osmosis pressure
VAN’T HOFF law

The laws of osmotic pressure are formally looks the same to the laws of perfect gases

\[ p_{\text{osmotic}} V = n RT \]

\[ p_{\text{osmotic}} = \frac{n}{V} RT \rightarrow p_{\text{osmotic}} = c R T \]

V: volume
n: mole fraction
T: temperature
c: concentration
R: universal gas constant

\[ p_{\text{osmotic}} \sim c \]

the osmotic pressure is linearly proportional to the concentration
The osmosis pressure
Classifying solutions on the basis of osmotic pressure

**HYPOTONIC**
(0,01 % NaCl, diluted)
lower concentration
\( C_{\text{outside}} < C_{\text{inside}} \)
higher osmotic pressure inside
\( P_{\text{outside}} < P_{\text{inside}} \)
Net water **IN**flux

**ISOTONIC**
(0,87% NaCl)
same concentration
\( C_{\text{outside}} = C_{\text{inside}} \)
same osmotic pressure
\( P_{\text{outside}} = P_{\text{inside}} \)
**No** net water flux

**HYPERTONIC**
(10% NaCl, concentrated)
higher concentration
\( C_{\text{outside}} > C_{\text{inside}} \)
higher osmotic pressure
\( P_{\text{outside}} > P_{\text{inside}} \)
Net water **OUT**flux

Red blood cells in variations environments
The osmosis pressure
Classifying solutions on the basis of osmotic pressure

**HYPOTONIC**
(0,01 % NaCl, diluted)

- lower concentration
  \[ C_{\text{outside}} < C_{\text{inside}} \]
- higher osmotic pressure inside
  \[ P_{\text{outside}} < P_{\text{inside}} \]

Net water **IN**flux
Haemolysis

**ISOTONIC**
(0,87% NaCl)

- same concentration
  \[ C_{\text{outside}} = C_{\text{inside}} \]
- came osmotic pressure
  \[ P_{\text{outside}} = P_{\text{inside}} \]

No net water flux

**HYPERTONIC**
(10% NaCl, concentrated)

- higher concentration
  \[ C_{\text{outside}} > C_{\text{inside}} \]
- higher osmotic pressure
  \[ P_{\text{outside}} > P_{\text{inside}} \]

Net water **OUT**flux

Red blood cells in variations environments

![Hypotonic](hypotonic.jpg)

![Isotonic](isotonic.jpg)

![Hypertonic](hypertonic.jpg)
Role of osmosis in the life of plant cells

Plant cells in various environments

Hypertonic: net water OUT flux

Isotonic: NO net water flux

Hypotonic: net water IN flux

PLASMOLYSIS!!!

the plasma membrane is pulled away from the cell wall

TURGOR PRESSURE

the plasma membrane is pushed to the cell wall

https://www.ck12.org/biology/osmosis/lesson/Osmosis-BIO
Osmosis in the medical practice

1. INJECTION, INFUSION
   ✓ Drugs are dissolved in physiological saline solution isotonic environment

2. TREATMENTS OF OEDEMAS, INFLAMED AREAS
   ✓ abnormal accumulation of fluid beneath the skin or in one or more cavities of the body that produces swelling (fluid accumulation)
   ✓ dextrane-solution /bitter salt (MgSO₄ – solution) based treatment → hypertonic environment is created (compared to the swollen areas) → induces water outflow from the swollen areas → reduced swelling

3. TREATMENT OF CONSTIPATION (laxative salts)
   ✓ laxatives salts are not absorbed by the large intestine → hypertonic environment is created in the large intestine → results is water influx into the large intestine → dilution of colonic content, facilitated excretion occur
Osmosis in the medical practice

4. **DIALYSIS:**
   - different particles can be separated from each other through the semipermeable membranes
   - pore diameter (size) of the membrane determines, which molecules can pass through the membrane
   - blood „filtering” through the semipermeable membrane

https://hu.wikipedia.org/wiki/Dial%C3%ADzis
Osmosis in the medical practice

4. DIALYSIS

4.1. HEMODIALYSIS

✓ treatment of patient with severe kidney disease
✓ remove soluble toxic chemicals for the body (pl.: proteins products, toxins, other waste product, BUT! essential plasma proteins, cellular elements of blood remain)

• long, tube shape semipermeable membrane e.g.: cellophane surrounded by dial solution
• composition of the dial solutions are different
• treatment: 4-8 h
• solution has to be changed frequently
• check ion-concentrations and metallic-ion-contaminations in the solution

Schematic diagram of haemodialysis („artificial kidney” instrument)

https://www.tankonyvtar.hu/
Overview of osmosis

- Osmosis = restricted diffusion
- Semipermeable membrane prohibits the movement of the particles
  SEMIPERMEABLE=allow small molecules transport, not the larger
  What does it mean?
  the diameter of pore determine, which particles can pass through the membrane
- Van’t Hoff law
- The osmotic pressure and its significance (rbc, medical application)
Thank you for your attention!

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