Reverse Osmosis (1)

Lecture 4

General Definition

- Membrane Processes include a broad range of ***seperation processes*** from filtration to ultrafiltration and reverse osmosis.
- Types of Membrane processes
- Microfiltration (MF)
- Ultrafiltration (UF)
- Nanofiltration (NF)
- Reverse Osmosis (RO)
- Dialysis / Electrodialysis (ED)

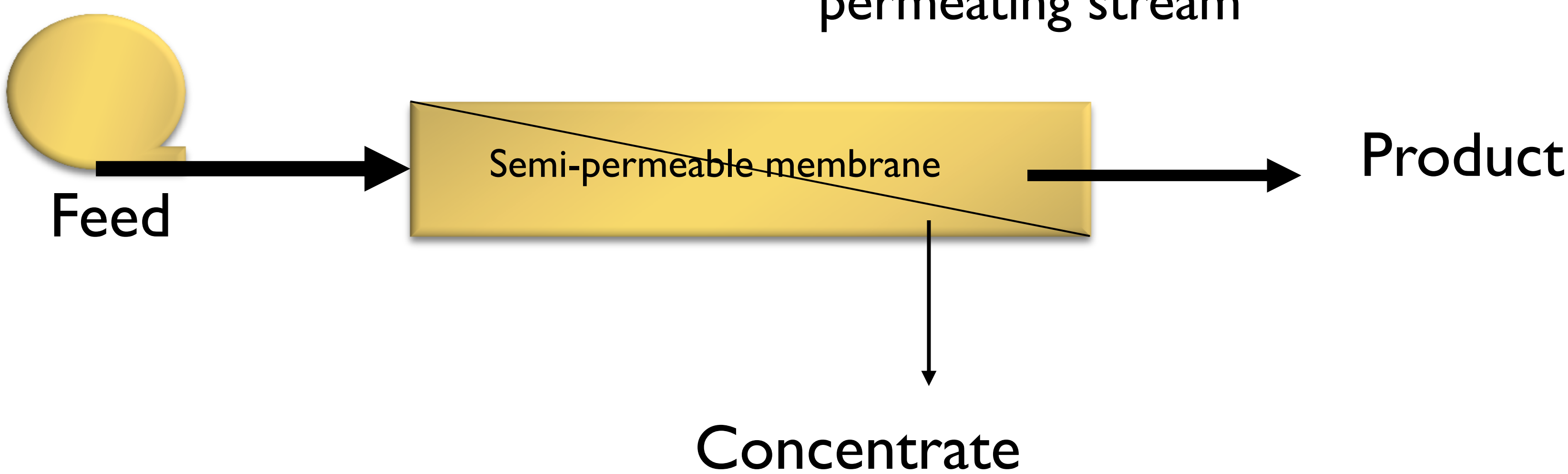
Examples for Applications of Membrane Processes

- Desalting seawater
- Treating brackish groundwater
- Waste water recovery
- Removing color, odor, and other organic contaminants

Process Configuration - General

Influent to the membrane module:
Feed water / feed stream

Liquid that passes through the semi-permeable membrane:
permeate / product stream / permeating stream

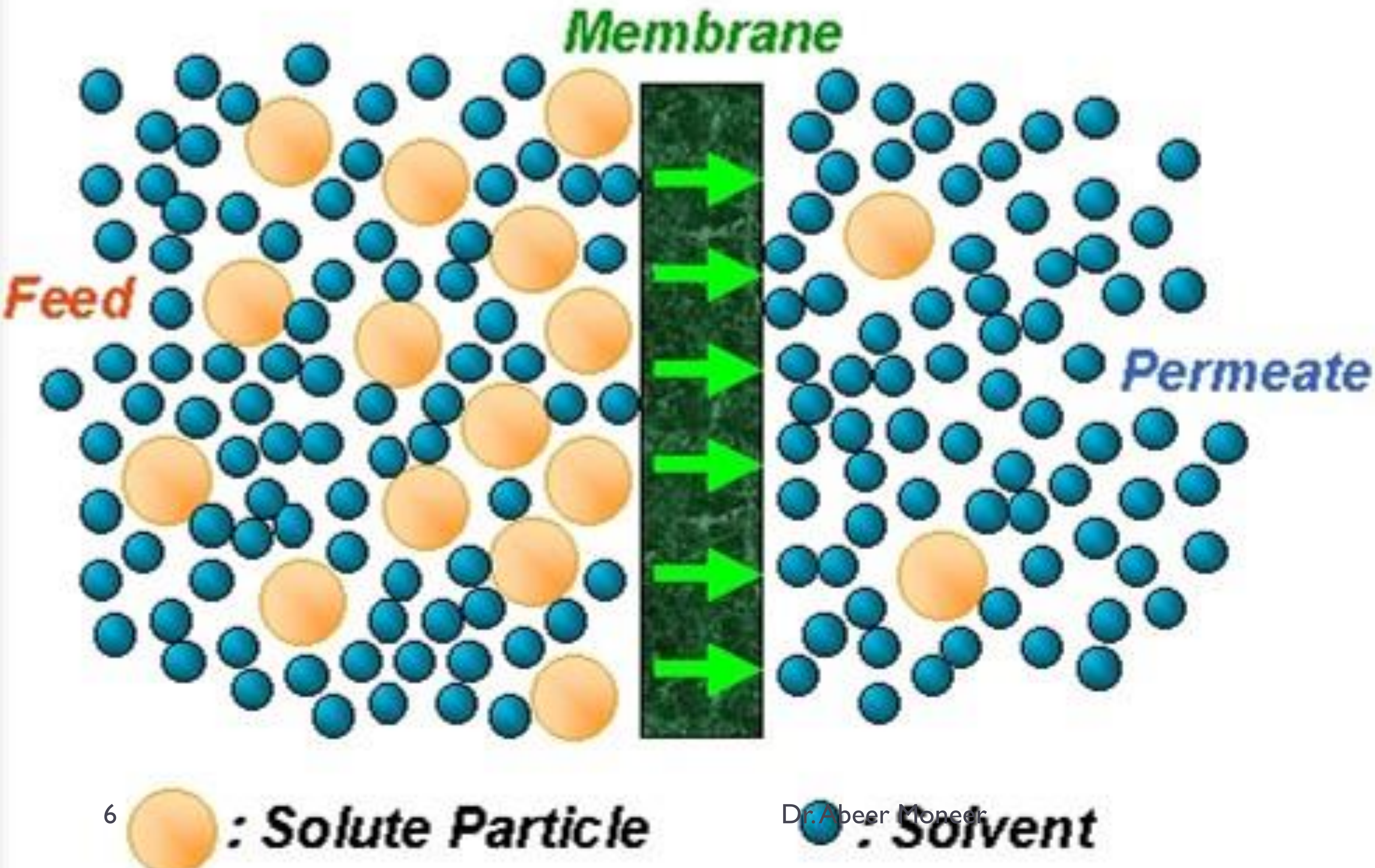


Liquid containing the retained constituents: Concentrate / retentate / reject / retained phase / waste stream

A membrane is a film.

- A semi-permeable membrane is a **VERY THIN** film that allows some types of matter to pass through while leaving others behind.

Membrane Separation



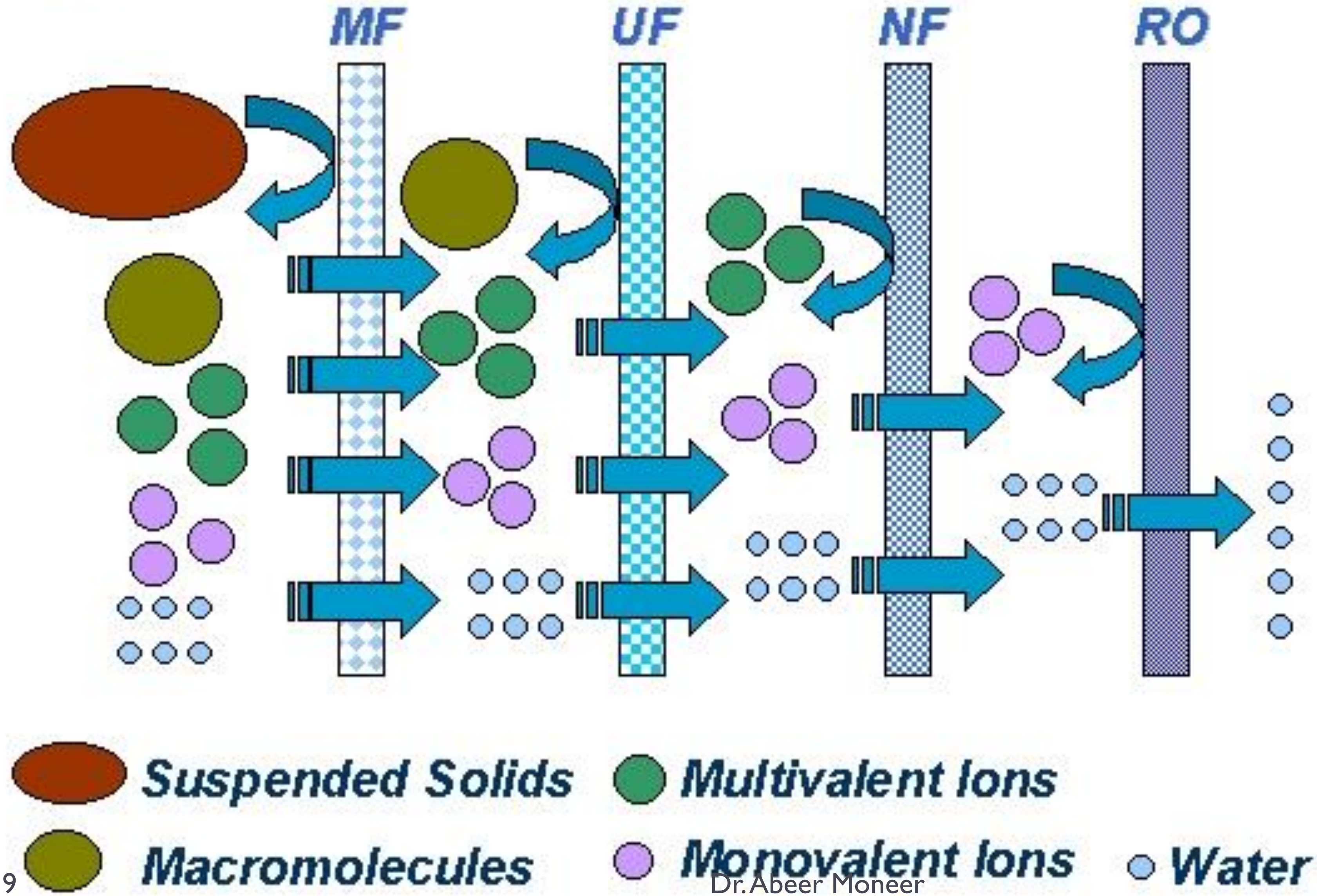
Factors affecting the removal efficiency

- Molecular size
- Polarity
- Molecular shape

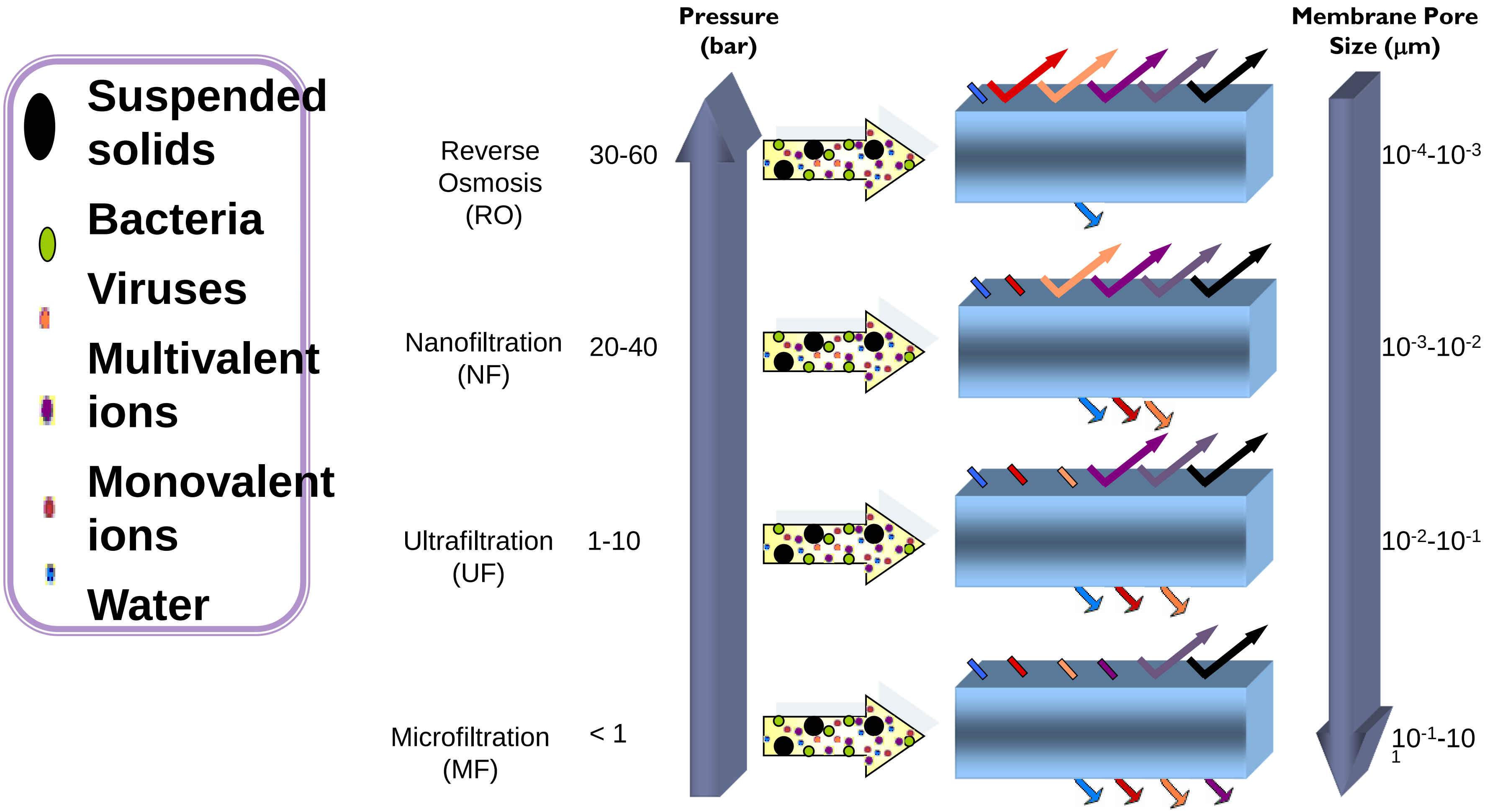
1. Membrane Processes

- Membranes play an important role in the **separation of salts.**
- This includes both the processes of **dialysis** and **osmosis** that occur in the **body.**
- Membranes are used in two commercially important desalting processes: **ED and RO**.
- Each process uses the ability of membranes to differentiate and selectively separate salts and water.
- However, membranes are used **differently** in each of these processes.

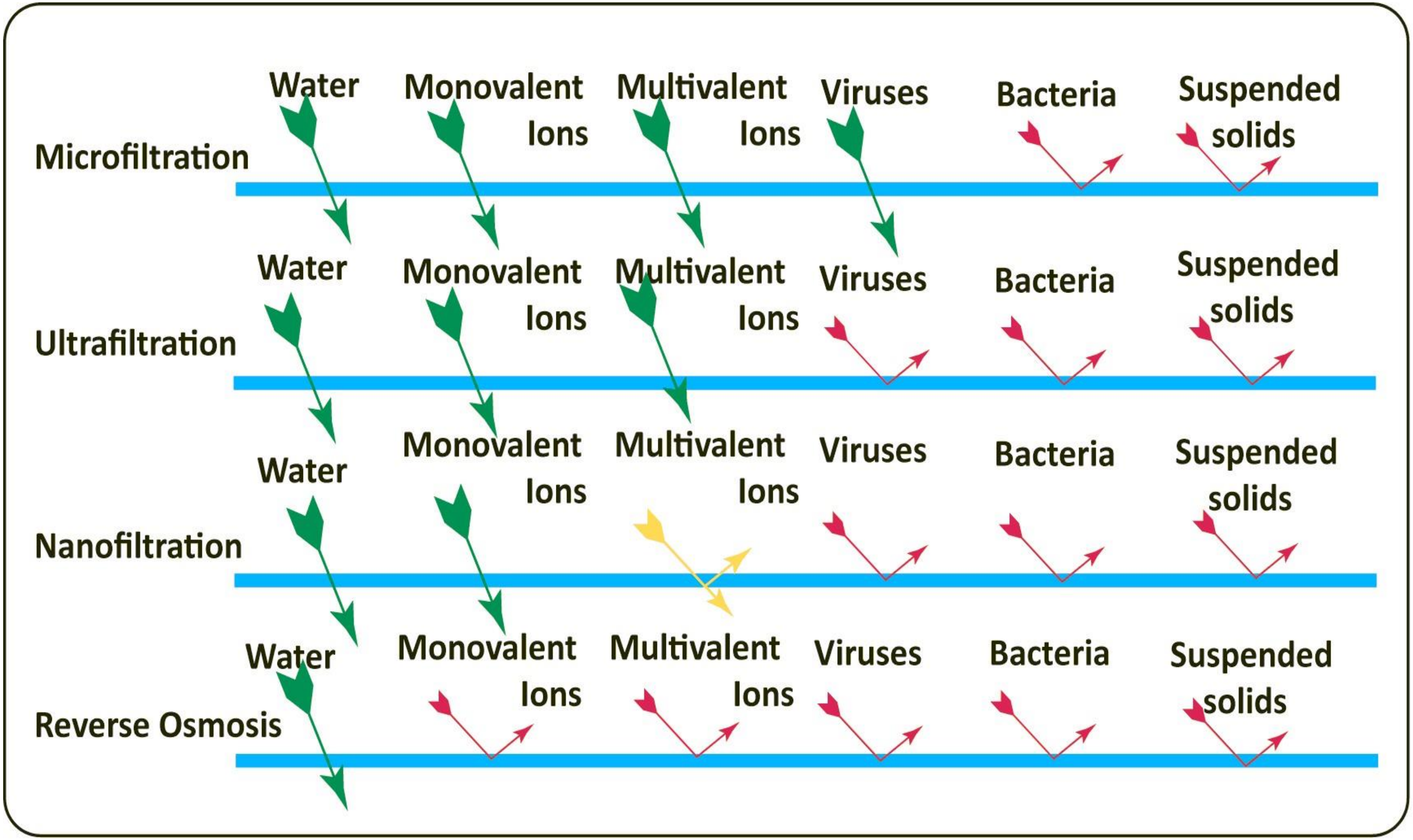
Types of Membrane



<u>Pressure driven</u> membrane processes are specially useful where a wide range of possible contaminants have to be removed over the entire removal spectrum i.e. **<u>macro particles to ionic species</u>**.



1. Membrane Processes



Membranes

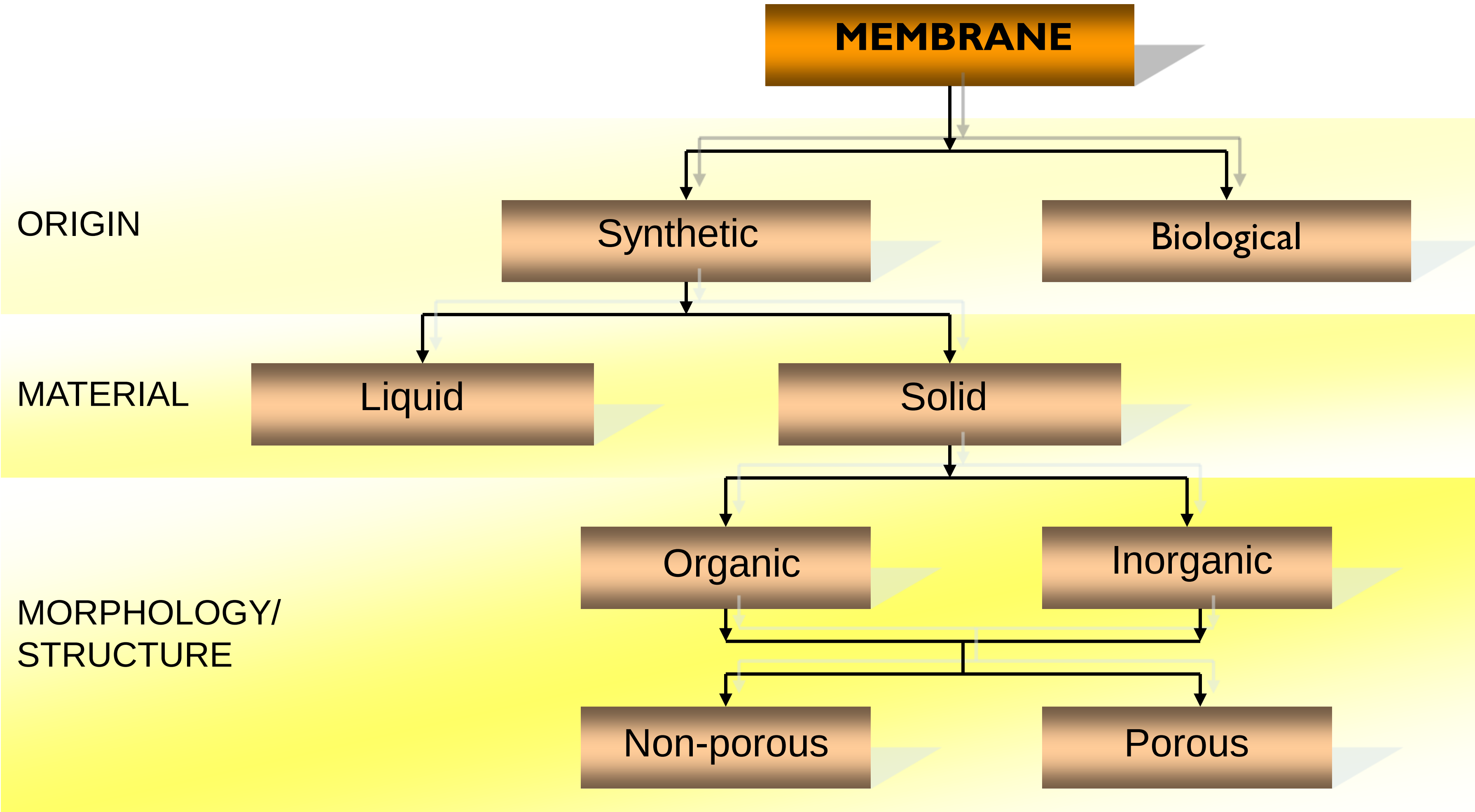
- The maximum separation reached in membrane processes depends on the **permeability** of the membrane for the feed solution components.
- A **permeable membrane allows** the passage of all **dissolved substances and the solvent**.
- A **semi-permeable membrane** is capable of transporting **different molecular species** at different rates under identical conditions.
- The ideal **semi-permeable membrane** in membrane processes is permeable to the **solvent only** but **impermeable to all solutes**.
- Membrane separation processes depend strongly on the **chemical nature of the membrane** materials and the **physical structure of the membranes**.

Characteristics of membranes

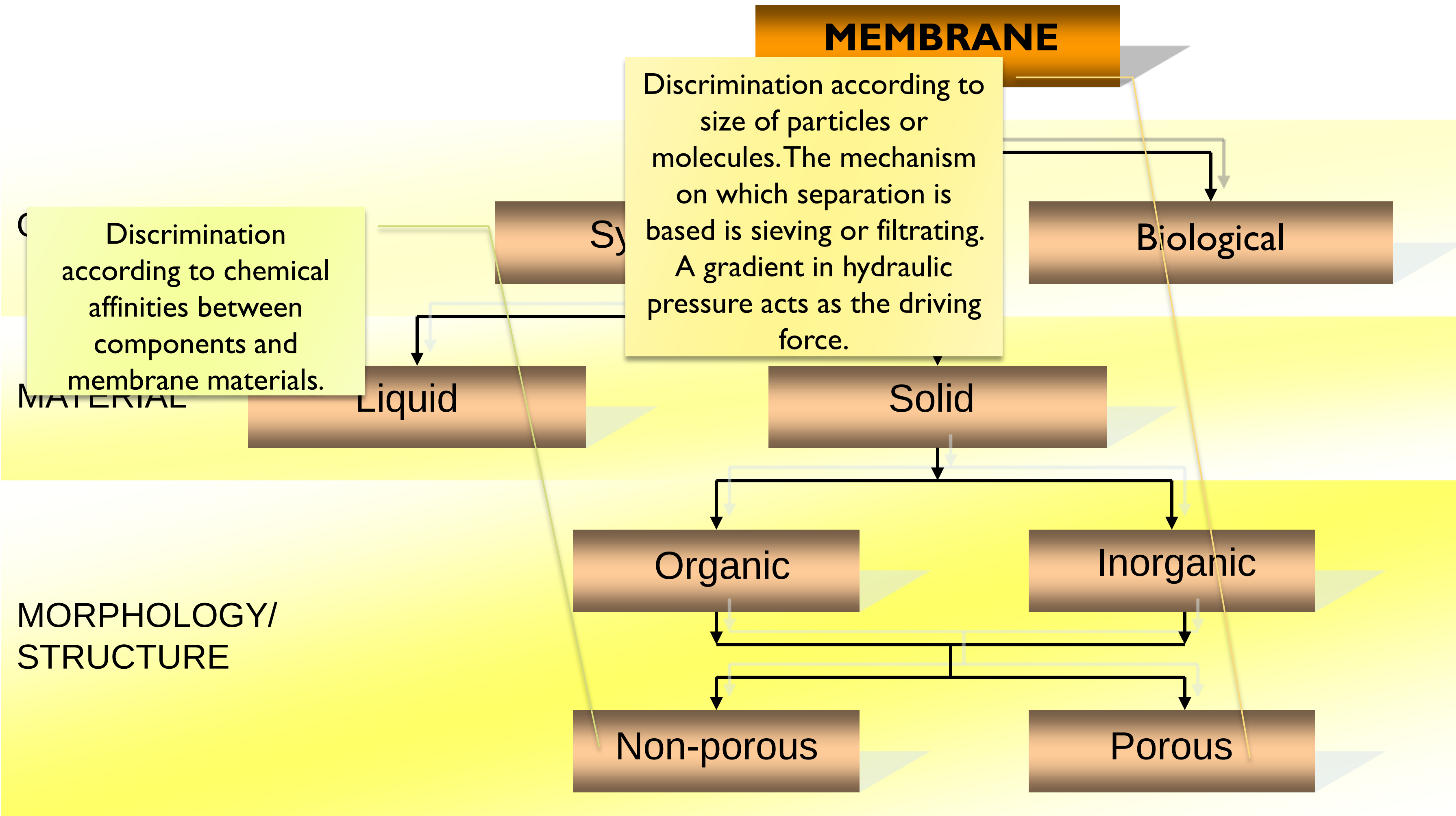
The following are some desirable characteristics of membranes:

- ✓Good permeability
- ✓High selectivity
- ✓Mechanical stability
- ✓Temperature stability
- ✓Ability to withstand large pressure differences across membrane thickness
- ✓Remain physically and chemically stable in a saline aqueous environment (stable over a wide range of pH values).
- ✓Be readily manufactured with reproducible characteristics.

MEMBRANE CLASSIFICATION



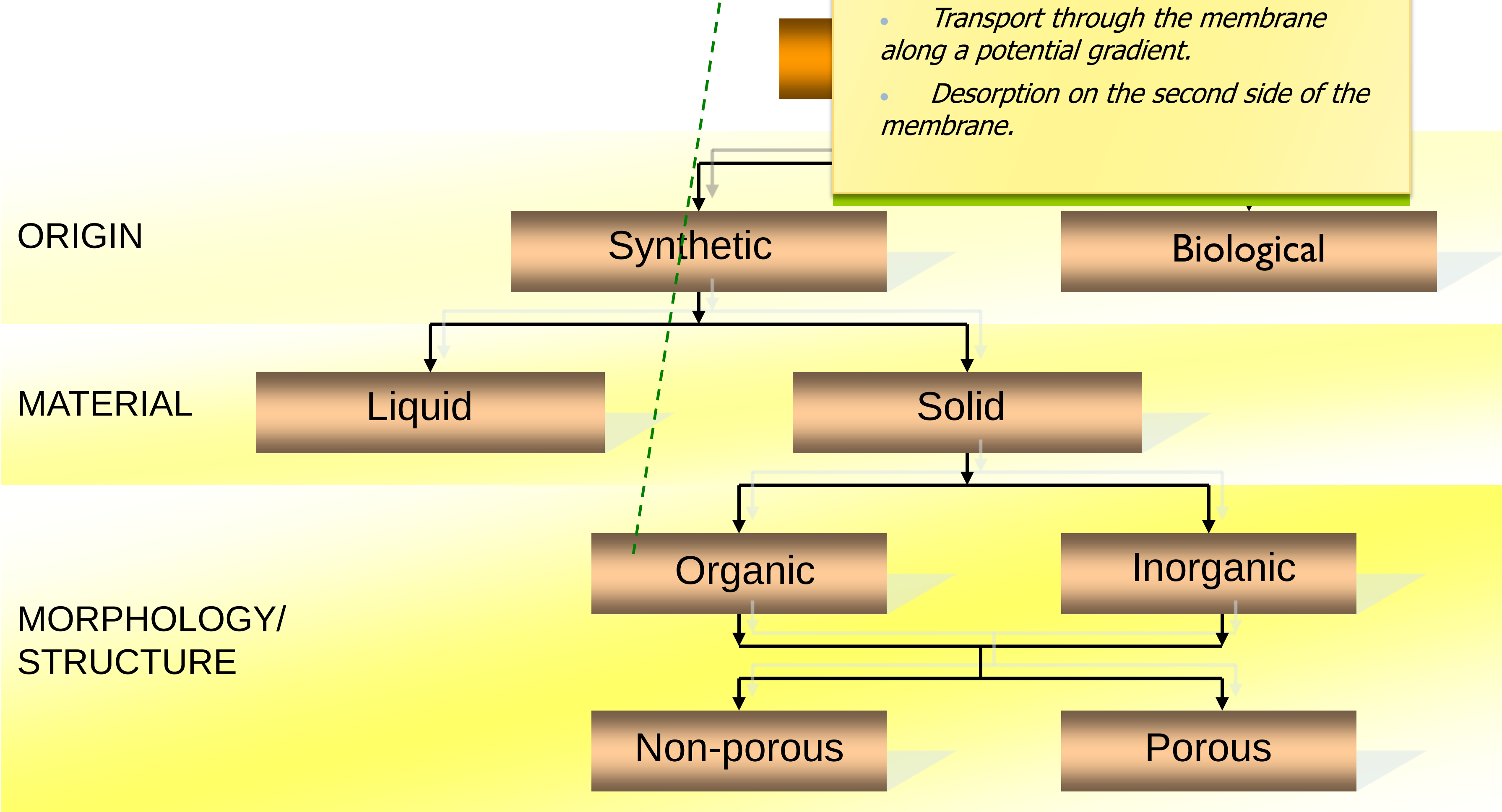
MEMBRANE CLASSIFICATION



MEMBRANE CLASSIFICATION

Mass transport through these membranes is described by the "solution-diffusion model" as follows:

- *Sorption of a component out of the feed mixture and solution in the membrane material.*
- *Transport through the membrane along a potential gradient.*
- *Desorption on the second side of the membrane.*



MEMBRANE CLASSIFICATION

According to the Physical Structure **("trans-wall symmetry")**

This quality describes the level of uniformity throughout the cross-section of the membrane.

SYMMETRIC (HOMOGENOUS)

Constructed by a single material and because of this reason, the membrane is uniform in density and pore structure throughout the cross-section.

ASYMMETRIC

May be either homogeneous or heterogeneous and are characterized by a density change given by the membrane material across the cross sectional area.

Skinned type: consist of a dense skinned layer used as primary filtration barrier and, a thick and more porous understructure that serves as support structure.

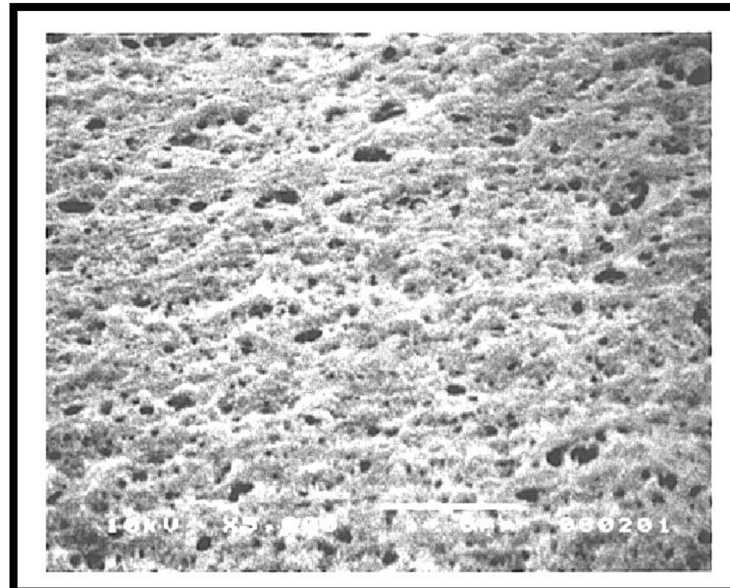
Graded density type: the porous structure gradually decreases in density from the feed to the filtrate side of the membrane.

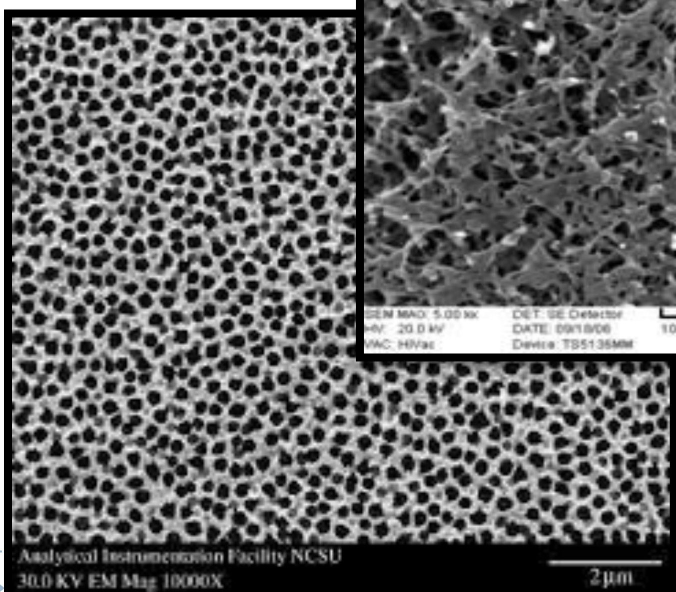
COMPOSITE (HETEROGENOUS)

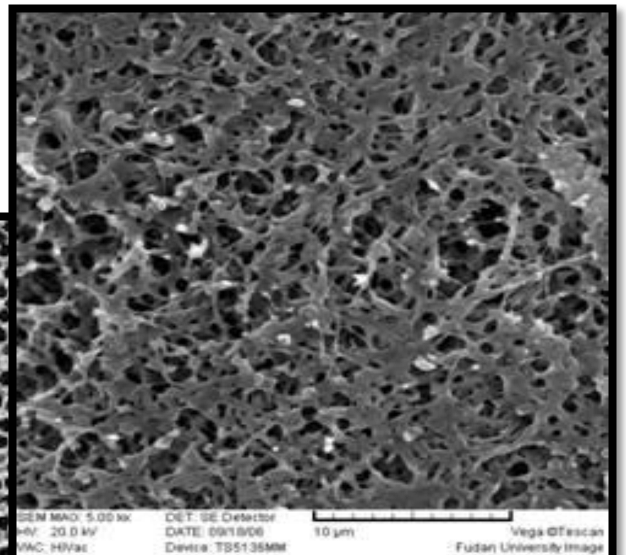
Constituted by different (heterogeneous) materials, the membranes have a thin, dense layer that serves as the filtration barrier. But, unlike skinned membranes, is made of different material than the porous substructure onto which it is cast.

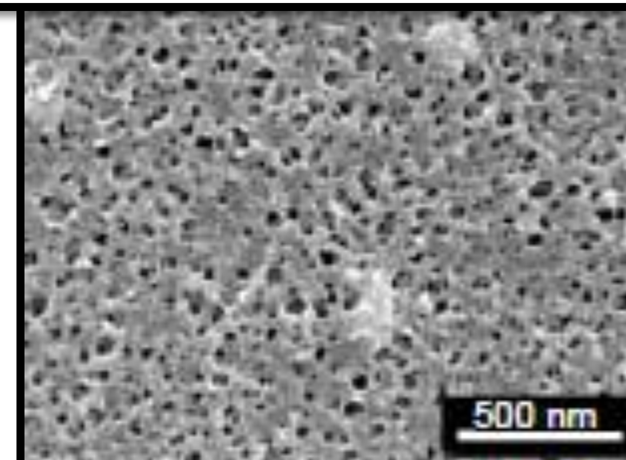
Symmetric Membranes

Constructed by a single material and because of this reason, the membrane is uniform in density and pore structure throughout the cross-section.



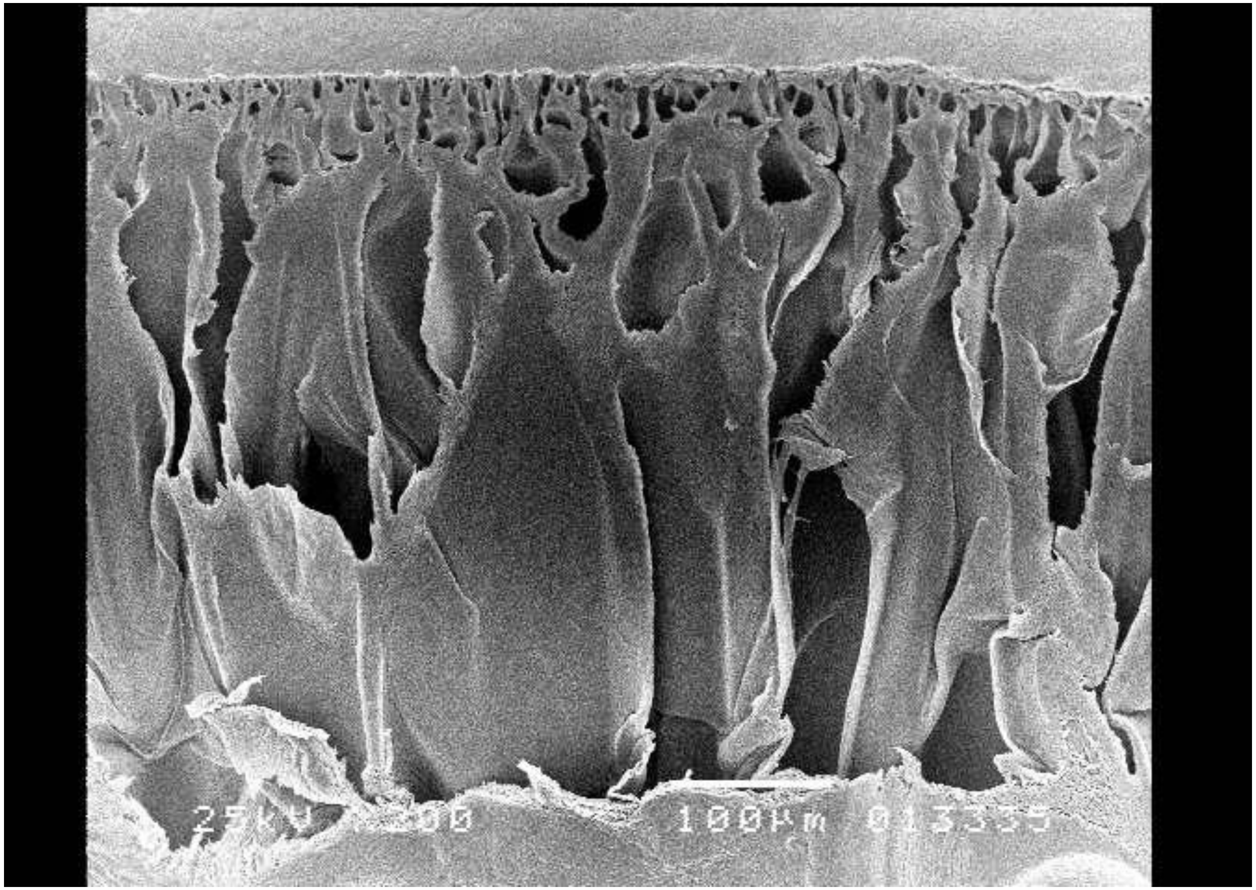






Asymmetric Membranes

Skinned type:
consist of:
i) A dense skinned layer used as primary filtration barrier and,
ii) A thick and more porous understructure that serves as support structure.

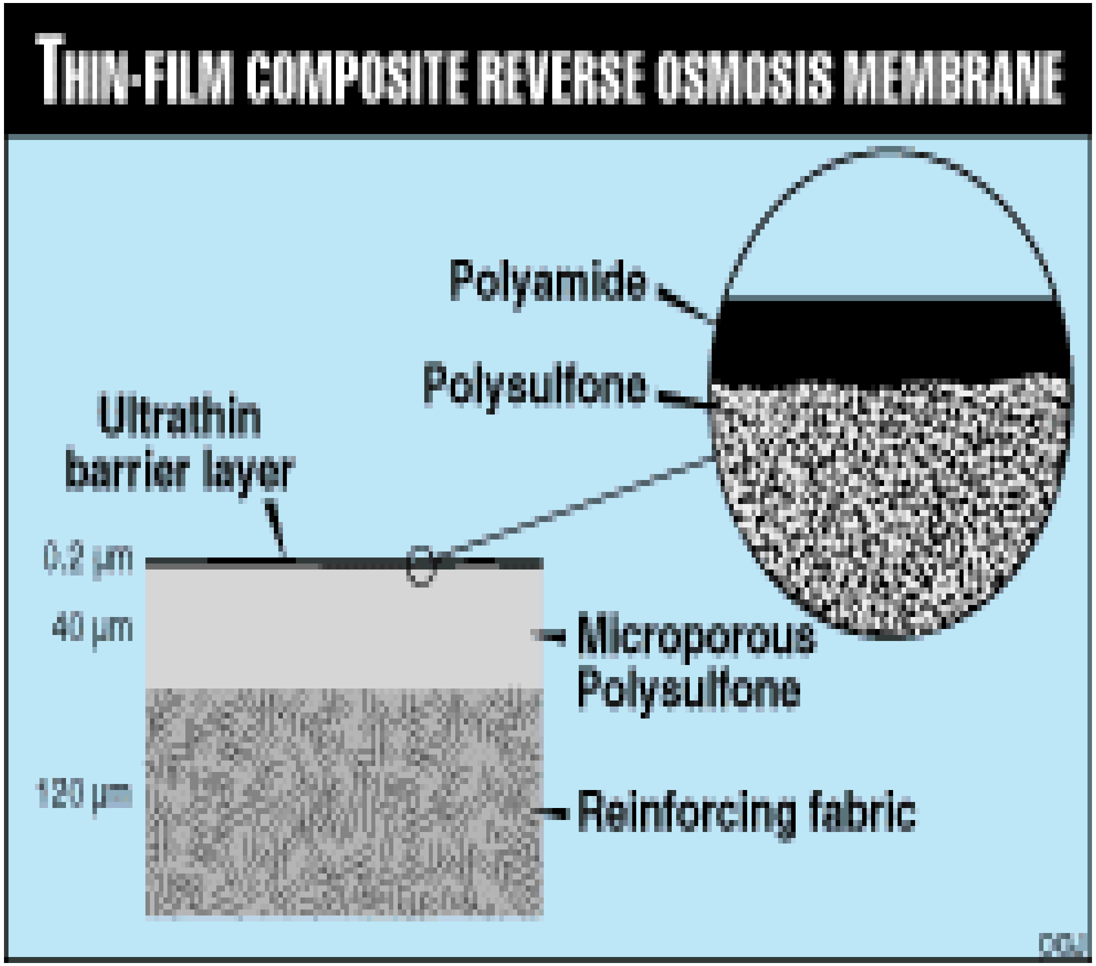


Composite membrane

Constituted by different (heterogeneous) materials, the membranes have:

A thin, dense layer that serves as the filtration barrier.

But, unlike skinned membranes, is made of different material than the porous substructure onto which it is cast.



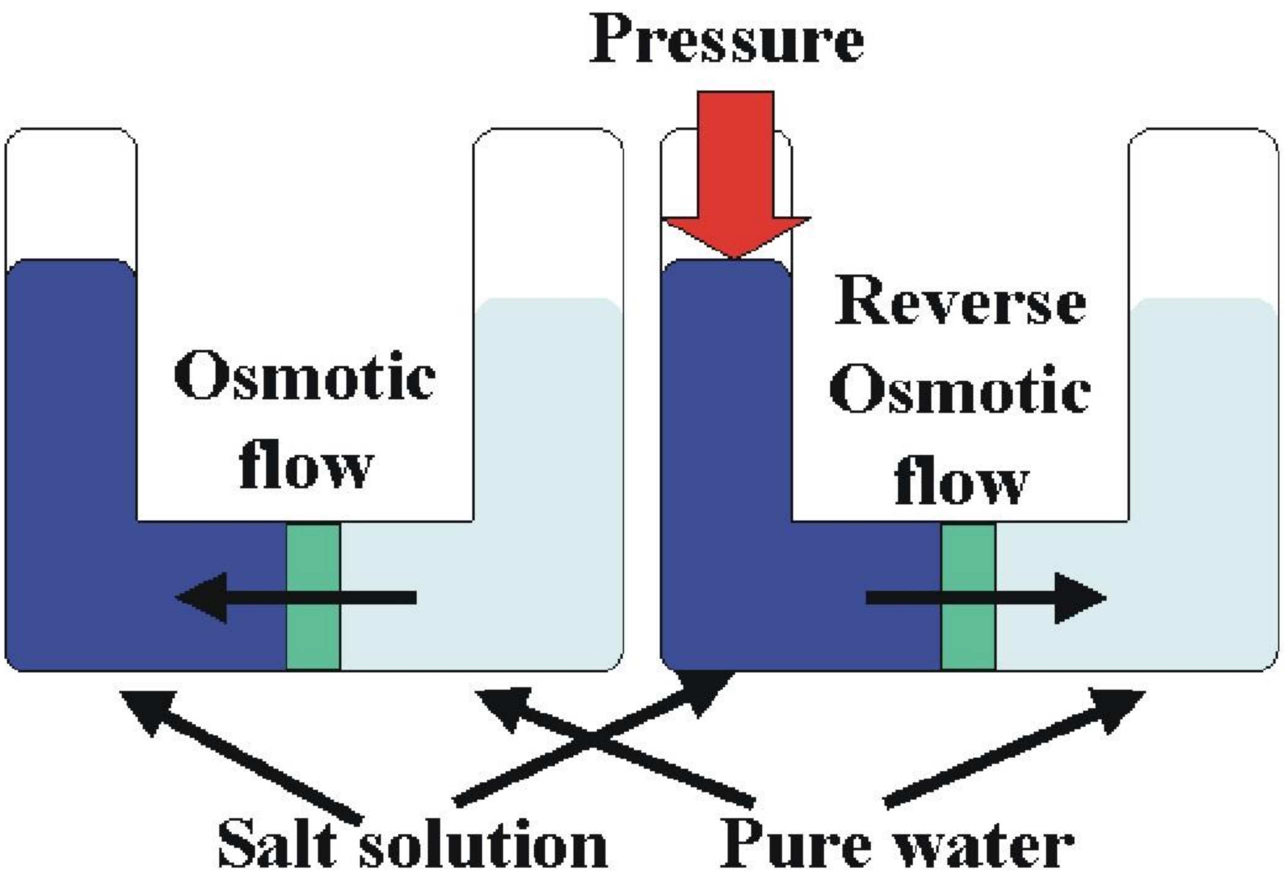
Casting Machine

1.Membrane Processes

Osmosis:

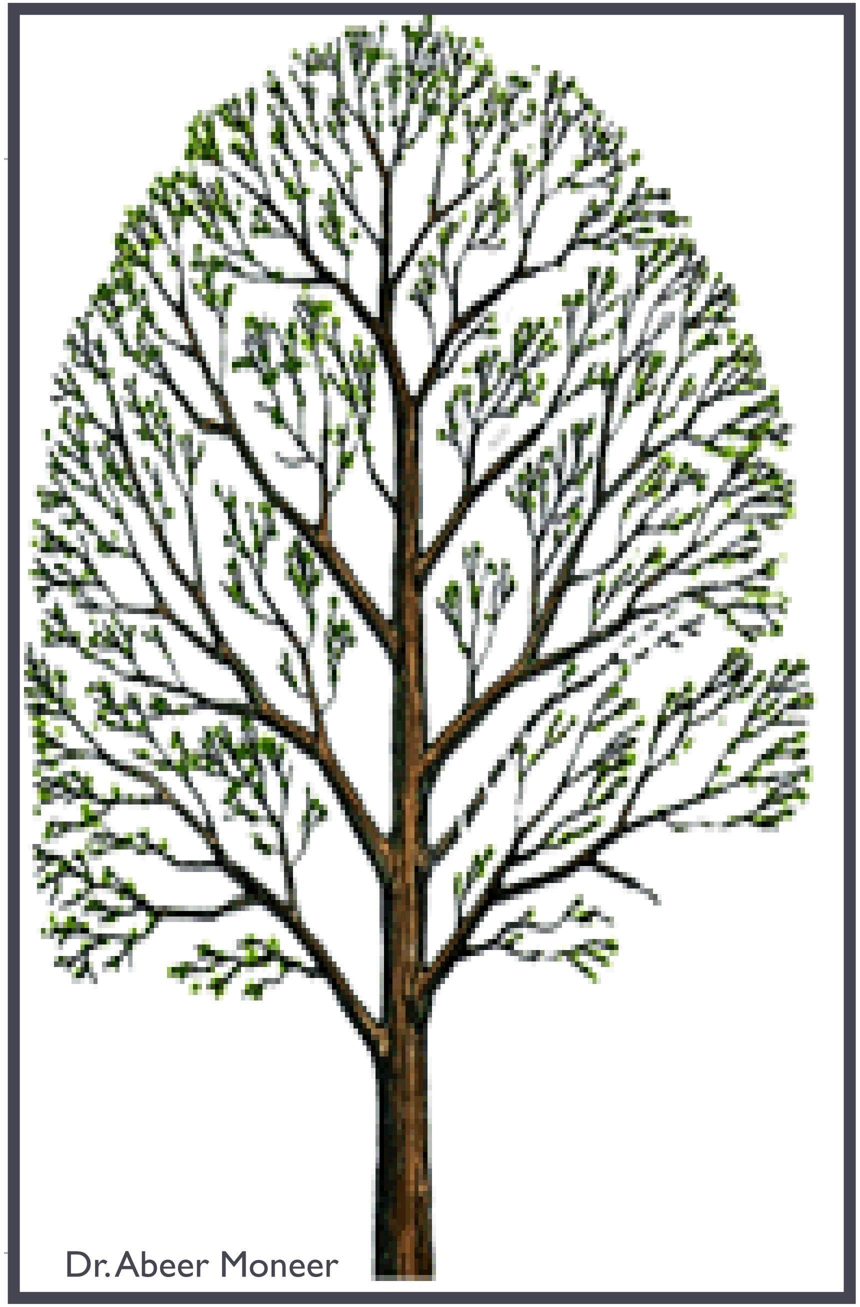
- If a **semi-permeable** membrane s**eparates** a solution from a pure solvent, or **2 solutions** of **different concentrations**, the tendency to equalize concentrations on both sides will result in a **flow of solvent from the less concentrated phase to the other** one (therefore, fresh water is lost).

1.Reverse Osmosis



Reverse Osmosis - a Natural Process

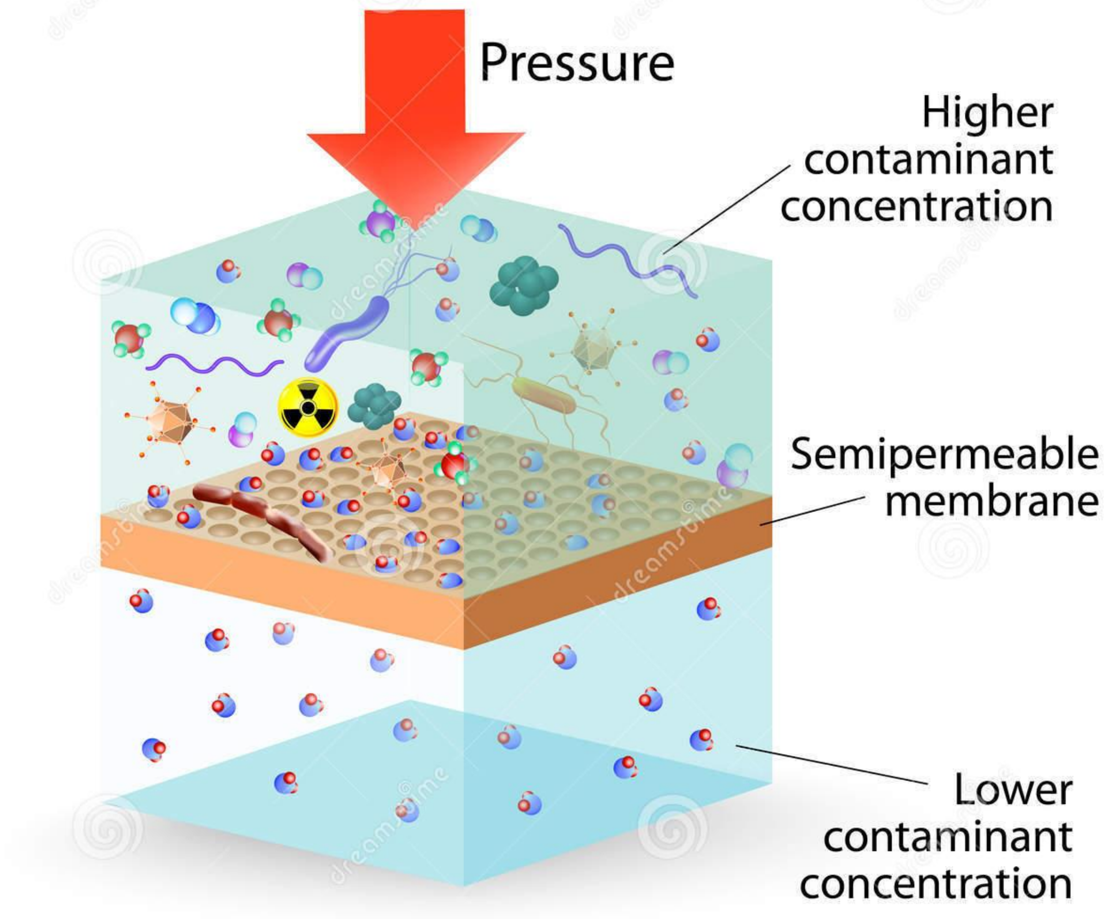
- Water is drawn from a low to a high concentration. Evapo-transpiration creates a suction which draws water up through the root hairs to the leaves.



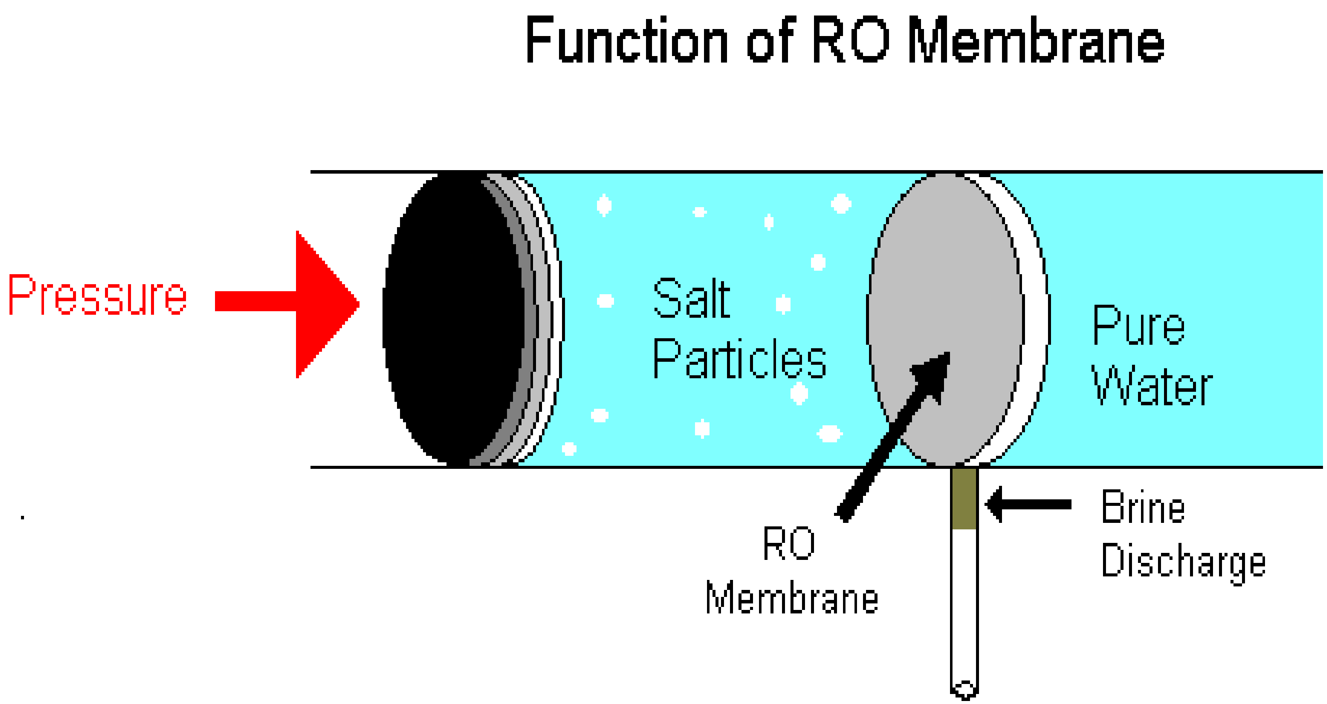
1.Reverse Osmosis

- If the flow is impeded by **excreting pressure** on the solution (of the high concentration) , the **rate of flow** from the less concentration side will be **decreased**.
- As the **pressure is increased**, a point will be found at which the **flow** is brought to a **complete stop** (the tendency to flow is in equilibrium with the opposing osmotic pressure).
- It is the property of the solution and can not depend in any way on the membrane as long as it is semi-permeable.
- **Further increase** in **pressure** causes **reversal** of the **osmotic flow** and pure solvent passes from the solution (of the high concentration) through the membrane into the solvent phase thereby increasing it.
- This is the basis of the RO method of desalination.

REVERSE OSMOSIS



1.Reverse Osmosis



1.Reverse Osmosis

- Osmotic pressures at 25°C

species	Concentration (mg/L)	Osmotic pressure (MPa)
NaCl	35,000	2.79
	5,000	0.39
	1,000	0.12
	500	0.09
Seawater	44,000	3.23
	32,000	2.31
Sucrose	34,000	0.26
	340,000	2.60
glucose	18,000	0.24
	90,000	1.21

2. Performance parameters

- The RO process is defined in terms of a number of variables, which includes:
- **Osmotic and operating pressure**
- **Salt rejection**
- **Permeate recovery**

Membrane manufacturing companies define system specifications in terms of the **feed quality**, which includes **salinity** and **temperature**.

2.1.Osmotic and operating pressure

- The **osmotic pressure, π,** of a solution can be determined experimentally by measuring the **concentration of dissolved salts** in the solution.
- The osmotic pressure is obtained from the following equation: $\pi = R\,T \sum X_i$

Where:

- π is the **osmotic pressure** (kPa).
- T is the **temperature** (K).
- R is the **universal gas constant**, 8.314 kPa m^3/kgmol K
- $\sum X_i$ is the **concentration** of all constituents in a solution (kgmol/m^3).

2.1.Osmotic and operating pressure

- Operating pressure is adjusted to overcome the adverse effects of the following:
- \- Osmotic pressure
- \- Friction losses
- \- Membrane resistance
- \- Permeate pressure

2.1.Osmotic and operating pressure

- If the **operating pressure** is set **equal** to the sum of the **former resistances** the net **permeate flow** rate across the membrane would be minimal or equal to **zero**;
- Therefore, the **operating pressure** is set at **higher value** in order to maintain economical permeate flow rate.

2.2. Salt rejection

- Salt rejection is defined by

$$SR = (1 - (Xp/Xf))*100$$

Where

SR = % **salt rejection**

Xp = **permeate salinity** (kg/m^3)

Xf = **feed salinity** (kg/m^3)

2.2. Salt rejection

- For example, a feed seawater with **42,000** ppm and a permeate with a salinity of 150 ppm gives a percentage salt rejection of **99.64%**.
- Similarly, for a brackish water feed with salinity of **5000** ppm and a permeate salinity of 150 ppm gives a percentage salt rejection of **97%**.
- The two cases indicate the **dramatic difference** between the **seawater and brackish water desalination membranes.**
- Current membrane technology provides salt rejection values above 99% for both seawater and brackish water membranes.

2.3. Permeate recovery

- **<u>Permeate recovery</u>** is another important parameter in the design and operation of RO systems. Recovery or **<u>conversion rate of feed water to product</u>** (permeate) is defined by

$$R = (M_p/M_f)*100$$

- where
- R is **<u>recovery rate</u>** (in %),
- M_p is the **<u>permeate water flow rate</u>** (kg/s), and
- M_f is the **<u>feed water flow rate</u>** (kg/s).

2.3. Permeate recovery

- The recovery rate affects salt rejection and product flow rate.
- As the **recovery rate increases**, the **salt concentration** on the feed-brine side of the membrane **increases**, which causes an increase in salt flow rate across the membrane.
- Also, **a higher salt concentration** in the feed-brine solution **increases the osmotic pressure**, **reducing** the **($\Delta P - \Delta \pi$)** and consequently **reducing the product water flow rate.**

2.3. Permeate recovery

- **Membrane recovery** for RO systems have **increased** over the years **from** lower values of **10-20%** **to** current higher values up to **50%.**
- This is achieved in part by **proper system design** and use of **multiple modules** of spiral wound membranes **within the same pressure vessel**.
- As for the hollow fiber membranes it common to use a single module within the same pressure vessel.

Questions

Answer with Yes or No and correct the false ones:

1. All types of membrane have the same properties.
2. The composite membranes composed of heterogeneous constituents.
3. The symmetric membranes have skin layer works as a filter layer.
4. A semi-permeable membrane is not capable of transporting different molecular species at different rates under identical conditions.
5. The membranes are synthetic materials without any natural basis.

Questions

6. The permeate salinity does not affect the % salt rejection.
7. Permeate recovery is the conversion rate of feed water to product.

<u>Answer the following questions:</u>

- Explain briefly, the reverse osmosis theory.
- What are the parameters affecting the permeate recovery.