River Valley High School
2025 JC1 H2 Biology

Lecture Topic 2: Cellular Transport

Name: _____ ( ) Class: 25J__ Date: _____

References

Title	Authors
Biology (9th edition)	Campbell and Reece
Biological Science 1: Organisms, Energy and Environment	Taylor, Green and Stout
AS Level Biology	Bradfield, Dodds and Taylor
Molecular Biology of the Cell (5th edition)	Alberts, Johnson, Lewis, Raff, Roberts and Walter

H2 Biology Syllabus 9477 (2025)

Candidates should be able to use the knowledge gained in the following section(s) in new situations or to solve related problems.

Related Topics	Concepts
Biomolecules of Life and Cellular Transport	Structures and roles of carbohydrates, lipids and proteins in living organisms
Organelles and Cellular Structure	Functions of membrane system and organelles
Communication and Equilibrium in Organisms	Roles of receptors on cell surface membrane

Learning Outcomes

1B. Biomolecules of Life and Cellular Transport

j. Explain the fluid mosaic model and the roles of the constituent biomolecules (including phospholipids, proteins, glycolipids, glycoproteins and cholesterol) in cell membranes.

k. Outline the functions of membranes at the surface of cells and membranes within the cell.

l. Explain how and why different substances move across membranes through simple diffusion, osmosis, facilitated diffusion, active transport, endocytosis and exocytosis.

Lecture Outline

I. Membrane Structure

A. Fluid Mosaic Model of Membrane Structure

B. Components of Biological Membranes

II. Membrane Function

III. Transport Across Membranes

A. Passive processes

1. Simple Diffusion
2. Facilitated Diffusion
3. Osmosis

B. Active processes

1. Active Transport
2. Bulk Transport (Endocytosis, Exocytosis)

Websites

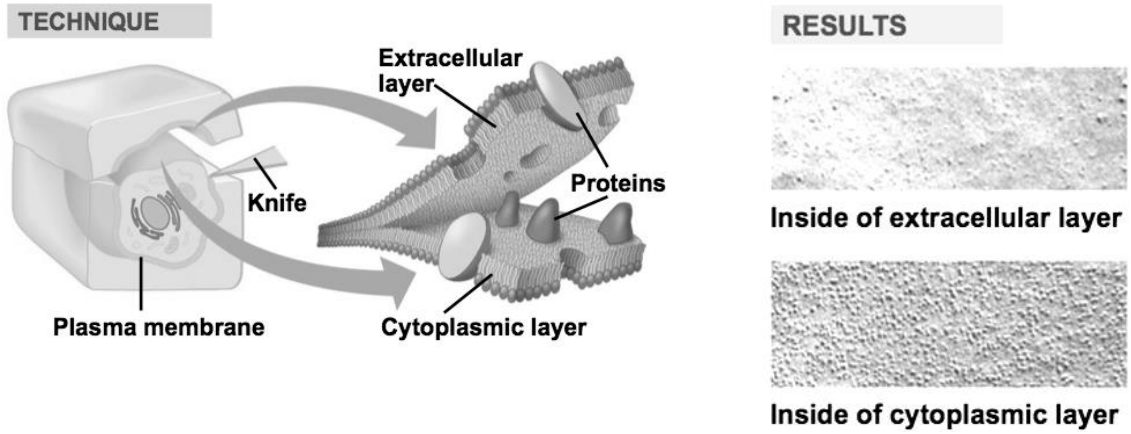
URL	Description
https://www.youtube.com/watch?v=nsklF1w4eok	This TED-Ed video provides an overview of the structure and function of the membrane and its components.
http://moleculesinmotion.com/jmol/boyer_completed/animations/membrane_transport/membrane_transport.htm *Note: you would need to use a laptop/desktop and download a chrome extension (e.g. "Flash Player for Chrome") to view the tutorial.	An interactive tutorial on the different mechanisms by which transport across membranes occurs. The tutorial contains animations for better visualisation, as well as quizzes to reinforce concepts.

I. Membrane Structure

A. Fluid Mosaic Model of Membrane Structure

Since 1917, various membrane models have been proposed; and the currently accepted model, though continually being refined, is the **fluid mosaic model**. This model was proposed by S.J. Singer and G. J. Nicholson in 1972, who described the membrane structure to follow a fluid mosaic model.

Evidence for the Fluid Mosaic Model

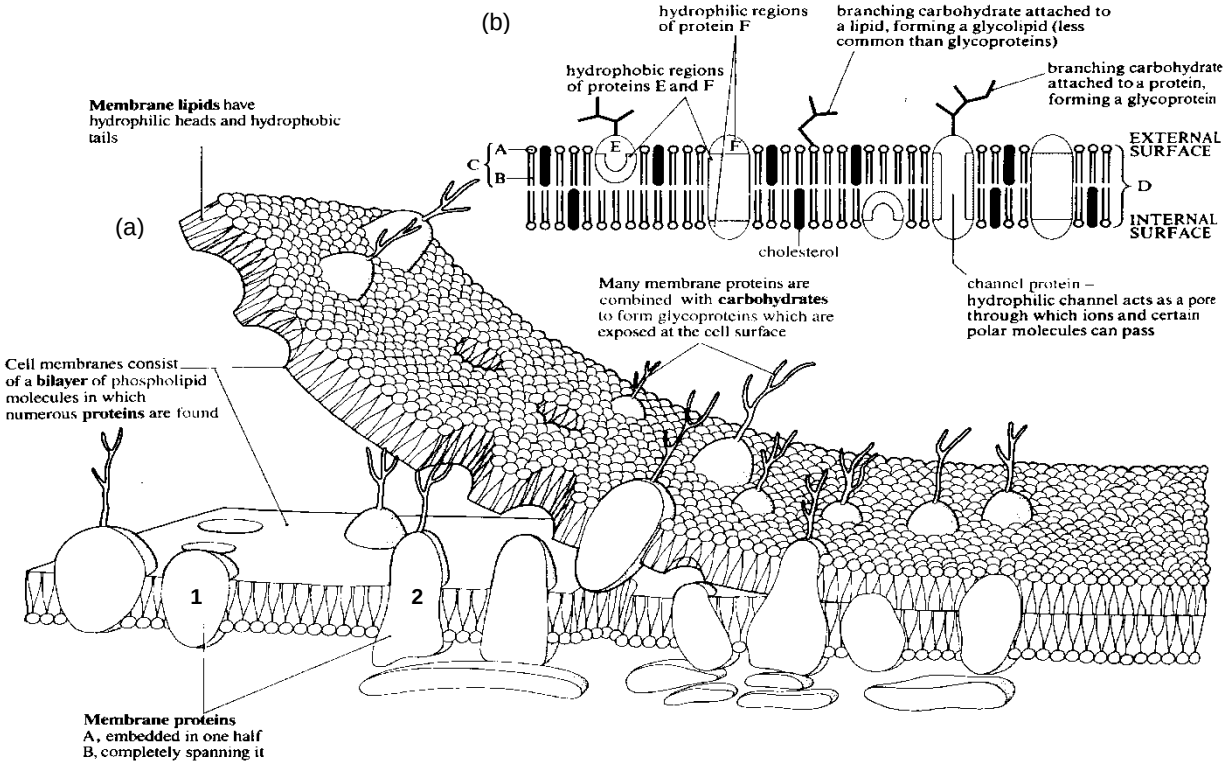


Freeze-Fracture Technique
Source: Biology, Pg 127.

Evidence for this model came from the **freeze-fracture technique**, together with **electron microscopy**. In this technique, a cell is frozen with liquid nitrogen and then "tapped" with a knife. This causes a fracture along the middle of the phospholipid bilayer and split the plasma membrane into two separated layers

When the inner surface of each layer of the plasma membrane is viewed under a scanning electron microscope, globular structures (the "bumps"), which are the same size as globular membrane proteins, can be seen scattered throughout. This provided evidence that proteins are interspersed and randomly embedded in the phospholipid bilayer.

Structure of the Fluid Mosaic Model



Fluid Mosaic Model of Membrane Structure

*(a) Three-dimensional illustration of the plasma membrane. **1** and **2** are transmembrane proteins.*
*(b) Two-dimensional illustration of the plasma membrane. **D** shows the phospholipid bilayer. **C** shows a phospholipid molecule which is made up of a hydrophilic phosphate head **A** and a hydrophobic hydrocarbon tail **B**.*
Source: Biological Science 1: Organisms, Energy and Environment, Pg 142.

1. The fluid mosaic model of biological membrane comprises of phospholipids that moves laterally within the layer, and proteins that moves laterally in the bilayer, making it fluid. Proteins are interspersed and randomly embedded in the phospholipid bilayer giving it a mosaic appearance.

2. The phospholipid bilayer is about 7 nm thick and is asymmetrical.
   - Two phospholipid layers may differ in phospholipid and protein composition.

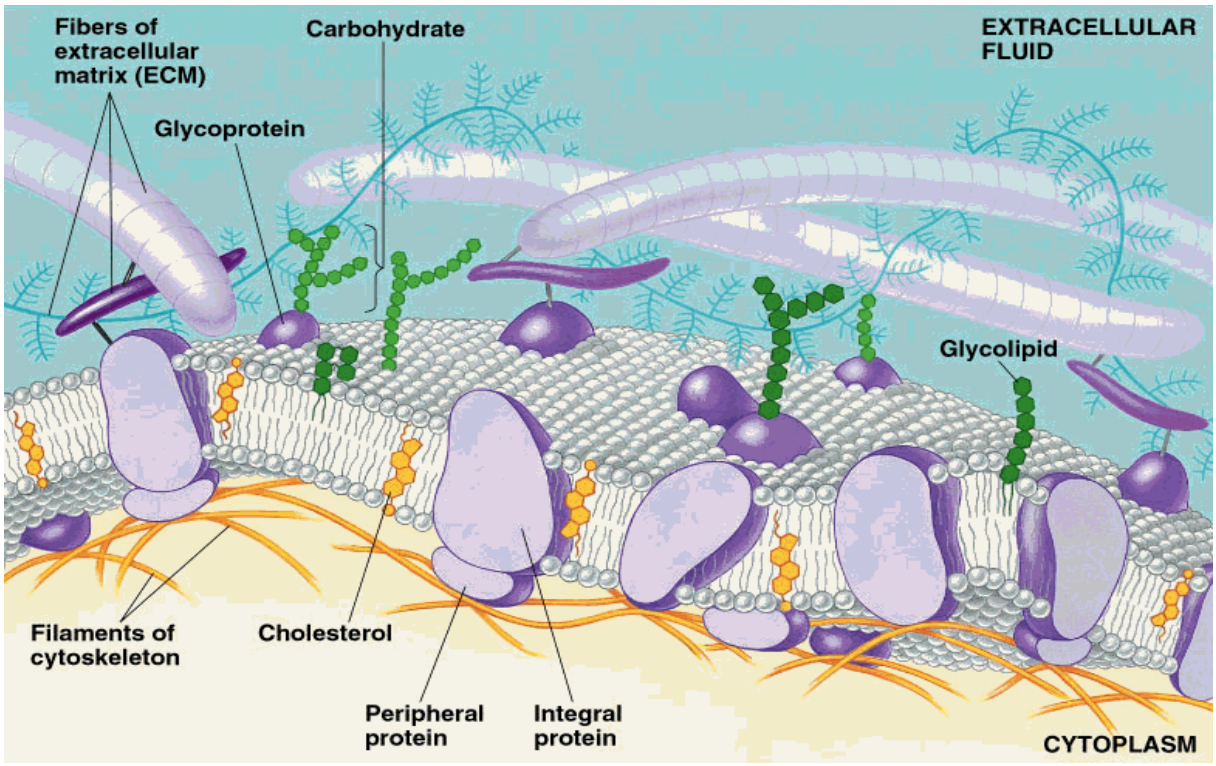
3. The hydrophilic phosphate heads of the phospholipids face outwards into the aqueous environments on both sides of the membrane. The non-polar, hydrophobic hydrocarbon tails face inwards and create a hydrophobic core that is shielded from aqueous environment.

4. Proteins may penetrate only part of the membrane, or through the entire length of the membrane. Their hydrophilic regions would protrude out of the membrane, and into the aqueous environments on either side.

B. Components of Biological Membranes

Biological membranes are assembled from four main components:

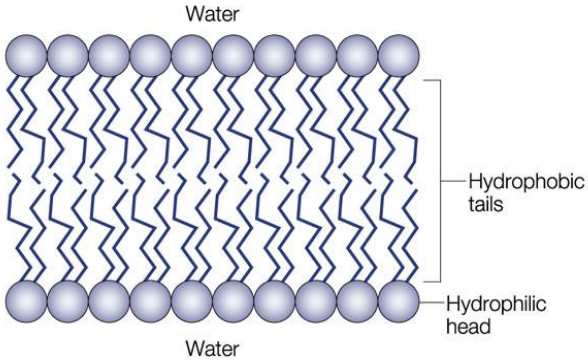
1. Phospholipids
2. Cholesterol (in animal cells only)
3. Proteins
4. Carbohydrates



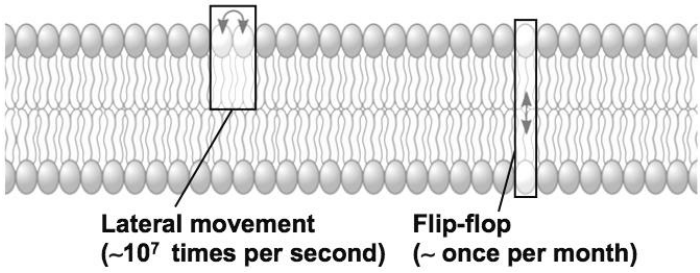
Structure of plasma membrane in an animal cell. Source: Biology, Pg 128.

1. Phospholipids

- Phospholipids have a hydrophilic phosphate head and two hydrophobic hydrocarbon tails.
- The shape and amphipathic nature of phospholipid molecules cause them to form **bilayers** spontaneously in aqueous environments.
  - The hydrophilic phosphate heads face the aqueous environment at each surface of the bilayer.
  - The hydrophobic hydrocarbon tails are shielded away from water in the interior of the membrane, forming a **hydrophobic core** that acts as a barrier to prevent the movement of polar molecules and charged ions across membrane .



Fluidity of membranes



Movement of phospholipids. Source: Biology, Pg 127.

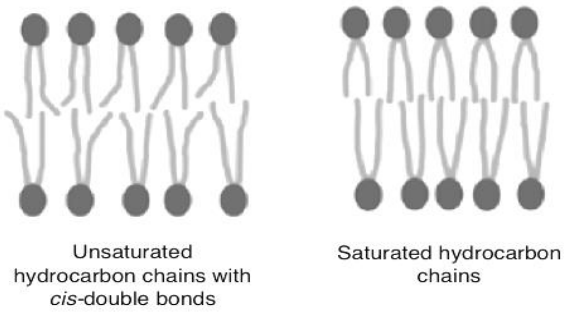
- Phospholipids are held together primarily by weak hydrophobic interactions. Hence, most of the phospholipid molecules and some of the membrane proteins can shift about laterally, in the plane of the membrane.
  - Flip-flopping transversely across the membrane, however, is rare since it would require the hydrophilic part of the molecule to cross the hydrophobic core of the membrane.
- The fluidity of membranes has to be precisely regulated. Certain membrane transport processes and enzyme activities cease when membrane viscosity exceeds a certain threshold level.

The fluidity of a phospholipid bilayer depends on four factors:

1. Temperature
   - As temperature decreases, membrane fluidity decreases.
   - A membrane remains fluid as temperature decreases, until a particular freezing point where the membrane solidifies. Upon this change of state, known as a *phase transition*, the phospholipids settle into a rigid, closely packed arrangement.

2. Fatty acid composition - **length** of hydrocarbon chains
   - Generally, the longer the fatty acid hydrocarbon chains, the higher the melting point of the membrane.
   - This is because a longer chain length increases the surface area of contact, thus increasing the tendency of the hydrocarbon tails interacting with one another via hydrophobic interactions.

3. Fatty acid composition - **degree of saturation** of hydrocarbon chains



   - **Unsaturated** fatty acid chains with *cis* carbon-carbon double bonds have **kinks**. These kinks hinder the hydrocarbon chains from packing closely together, thus increases membrane fluidity.
   - **Saturated** fatty acid chains are long and straight hydrocarbon chains. This facilitates close packing, thus decreases membrane fluidity.

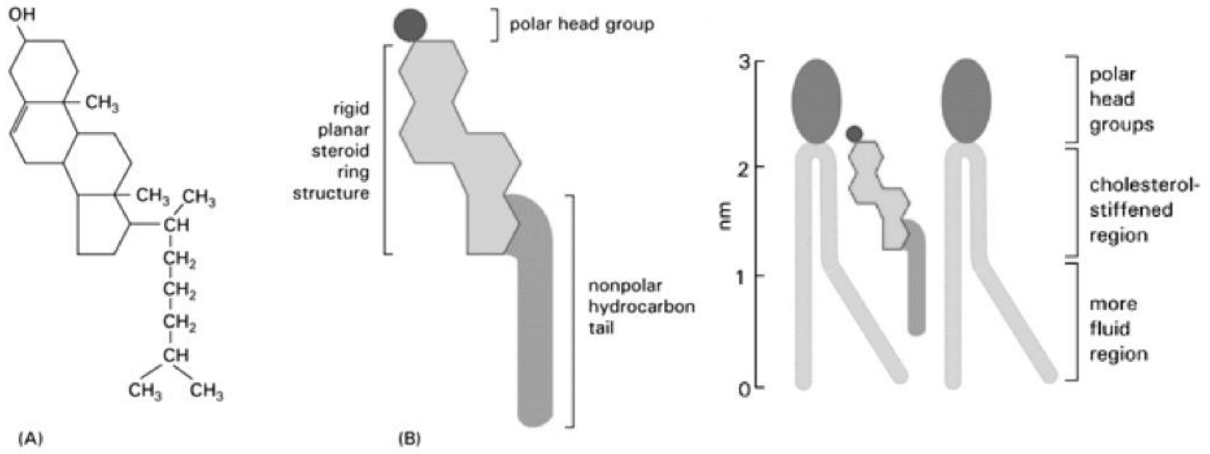
- **Application:**
  Organisms adjust the fatty acid composition of their membrane phospholipids to adapt to changing temperature.
  - In many plants that tolerate extreme cold (e.g. winter wheat), the percentage of unsaturated phospholipids (especially those with *cis* carbon-carbon double bonds) increase in autumn to increase membrane fluidity during low winter temperatures.
  - This approach is also taken by bacteria, yeasts and other unicellular organisms whose temperatures fluctuate frequently with that of their environment.

4. Amount of Cholesterol (for membranes in animal cells)

2. Cholesterol (in animal cells only)

Cholesterol is a major constituent of membranes in animal cells, where it serves as the key regulator of membrane fluidity. Plant cells lack cholesterol, but contain related compounds, sterols, that fulfil a similar function.

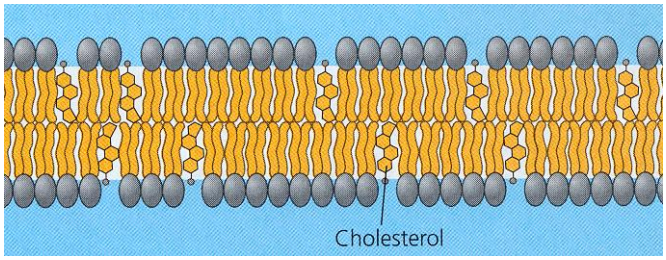
Cholesterol contains a hydrophilic OH group, but most of the molecule is hydrophobic. When present in membranes, it is therefore commonly wedged between phospholipid molecules, with its OH group aligning with the phosphate heads of the phospholipids, and the remaining hydrophobic portion tucking into the hydrophobic core of the membrane.



The structure of cholesterol, and its orientation in a lipid bilayer.

*Cholesterol is represented **(A)** by a formula, **(B)** by a schematic drawing. The diagram on the right is a schematic drawing of a cholesterol molecule interacting with two phospholipid molecules in one monolayer of a lipid bilayer. Source: Molecular Biology of the Cell, Pg 620.*

The presence of cholesterol exerts the following effects on membranes:



Cholesterol within the animal cell membrane

1. Membrane fluidity

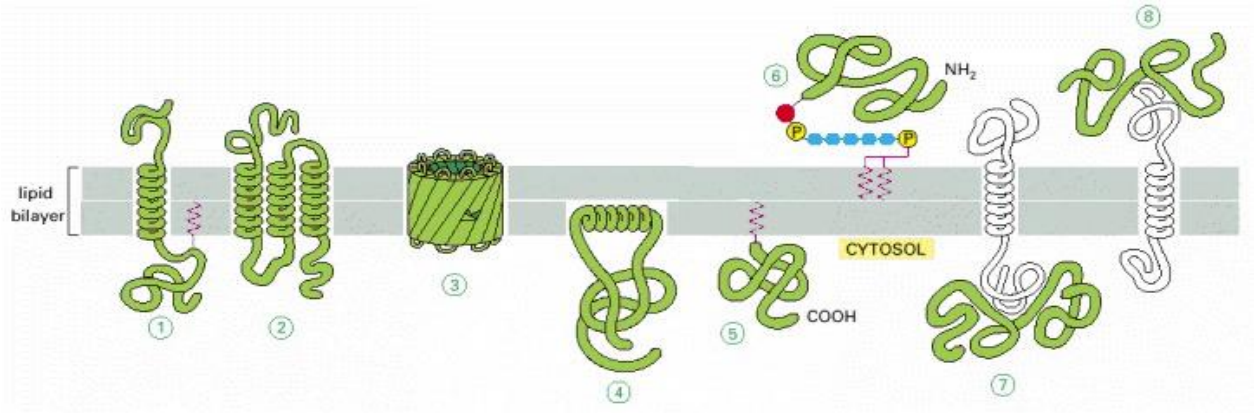
   - At higher temperatures, e.g. the human body temperature of 37°C, cholesterol limits fluidity. This is because cholesterol partly immobilises adjacent phospholipid molecules, thus restraining their mobility. This contributes to membrane stability at higher temperatures.
   - At low temperatures, cholesterol interferes with the close packing of the phospholipids, therefore enhancing membrane fluidity.
   - Hence, cholesterol acts as a "temperature buffer" for the membrane, resisting changes in membrane fluidity caused directly by changes in temperature.

2. Membrane permeability

   - The presence of cholesterol limits the permeability of membranes to charged ions and small polar molecules. It does so by filling in spaces between hydrocarbon chains of phospholipids, thus making it more difficult for such solutes to pass through the bilayer.

3. Proteins

Two major groups of membrane proteins exist: **Integral** proteins and **Peripheral** proteins.



Various ways in which membrane proteins associate with the lipid bilayer.

1. **Integral (intrinsic) proteins**

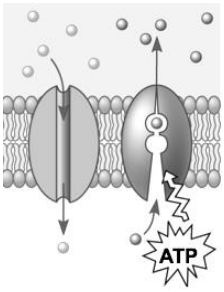
   - These are proteins that penetrate the hydrophobic core of the phospholipid bilayer.
   - Many integral proteins are **transmembrane proteins** that span the entire width of the membrane; others extend only partially into the hydrophobic core.
   - They are held in place within the membrane by hydrophobic interactions between their hydrophobic regions and the hydrophobic hydrocarbon tails of the phospholipids.
   - Their hydrophilic portions interact with the phosphate groups of the phospholipids and the aqueous environment on either side of the membrane.

2. **Peripheral (extrinsic) proteins**

   - These are proteins that are only loosely bound to the membrane surface, and are not embedded in the phospholipid bilayer.
   - These proteins tend to be rich in hydrophilic amino acid residues to allow for interactions with the surrounding aqueous environment, and the hydrophilic portion of the membrane.

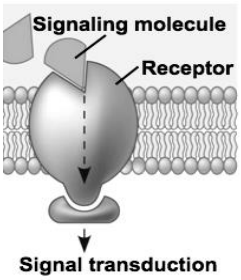
Functions of membrane proteins include:

1. Transport



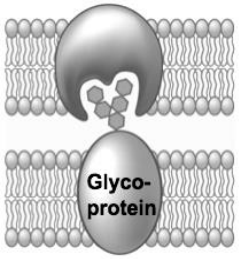
- Some transmembrane proteins, called **channel proteins**, provide a hydrophilic channel across the membrane that is selective for a particular substance (e. g. water, ions and small polar solutes).
- Other integral proteins, called **carrier proteins**, bind specific substances and transport them across the membrane by changing conformation. Sometimes, this transport process requires energy (obtained via hydrolysis of ATP).

2. Signal transduction



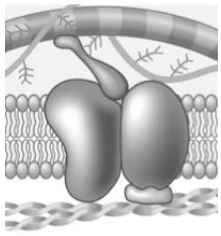
- Some membrane proteins serve as **receptors** for chemical signalling among cells.
- These proteins have a highly specific binding site that is complementary in shape to a particular chemical messenger (e.g. hormone).
- Binding of the chemical messenger may cause a change in conformation of the protein, which enables the protein to relay the message to the inside of the cell (usually via binding to a cytoplasmic protein).

3. Cell-cell recognition



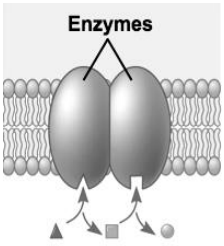
- Some membrane glycoproteins serve as **cell surface markers** that are specifically recognised by membrane proteins of other cells.
- This is crucial in the sorting of cells into various tissues and organs in an animal embryo.
- It is also the basis for the rejection of foreign cells (bearing foreign cell surface markers) by the immune system.

4. Attachment to the cytoskeleton and extracellular matrix (ECM)



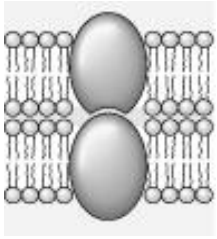
- Structures of the cytoskeleton may be non-covalently bound to membrane proteins.
- This helps to maintain cell shape and stabilises the location of certain membrane proteins.

5. Enzymatic activity



- Some membrane proteins are enzymes that catalyse metabolic reactions.
- Their active sites are exposed to the aqueous environment on either side of the membrane, depending on the location of the particular protein.
- In some cases, several enzymes in a membrane are organised as a team that carries out sequential steps of a metabolic pathway

6. Intercellular joining (Cell-cell adhesion)



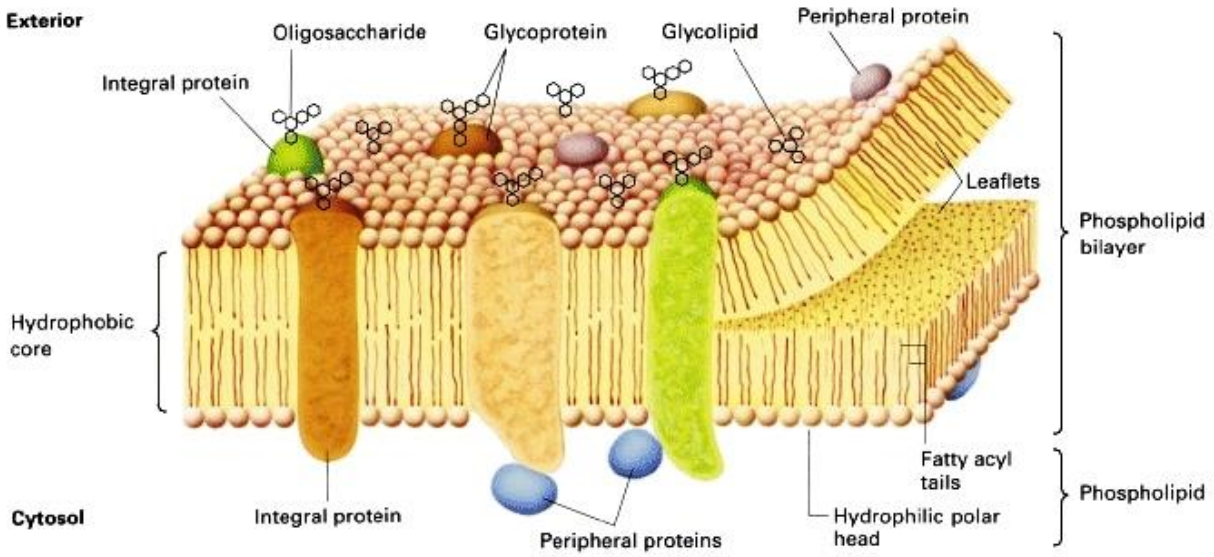
- Membrane proteins of adjacent cells may hook together in various kinds of junctions, such as gap junctions or tight junctions to form tissues.

4. Carbohydrates

Membrane carbohydrates are usually short, branched chains of fewer than 15 monosaccharide units. Most are covalently bonded to proteins, forming **glycoproteins**. Some are covalently bonded to lipids, forming **glycolipids**.

These oligosaccharide attachments are enormously diverse in their structure – they are often branched, and the sugar units can be bonded together by various covalent linkages.

This allows glycoproteins and glycolipids to take on a huge variety of specific shapes that can undergo specific interactions with other molecules for the various functions they play in cells.



Function of glycoproteins and glycolipids

Glycoproteins and glycolipids are abundant on the plasma membrane, especially on the side facing the exterior of the cell. On the plasma membrane, they play diverse functions such as:

1. Serving as specific cell surface markers for cell-cell recognition processes
   - e.g. in the interaction between antibodies and antigens in the immune system; binding of sperm to egg for fertilisation;
2. Cell-cell adhesion for purposes such as forming tissues
3. Serving as specific receptor sites for hormones and neurotransmitters
4. Protecting cells against mechanical damage
5. Keeping various other cells at a distance, preventing unwanted protein-protein interactions

II. Membrane Function

Biological membranes play the following roles in cells:

1. **Acting as a boundary:**

   - **A boundary of the organelles:** Separates organelles from the cytosol.
   - **A boundary between intracellular and extracellular environment**: The plasma membrane separates the internal and external environments of the cell. This maintains a distinct and constant internal environment, which is essential for a cell to function efficiently.

2. **Selective barrier that regulates the passage of substances into and out of cells and organelles**

   - Membranes are selectively permeable due to

     i) the hydrophobic core of the phospholipid bilayer; and

     - The **hydrophobic core** of the phospholipid bilayer allows small, non-polar and uncharged molecules (e.g. hydrocarbons, carbon dioxide, oxygen) to diffuse across, through transient gaps. However, it impedes the direct passage of charged ions and polar molecules.

     ii) specific transport proteins built into the membrane.

     - Transport proteins (channel and carrier proteins) serve to transport specific ions and polar molecules across the membrane.

   - Phospholipid molecules shift about laterally in the plane of the membrane occasionally creates transient 'gaps' that allow for movement of small, polar molecules across the membrane.

3. **Cell-cell recognition and adhesion**

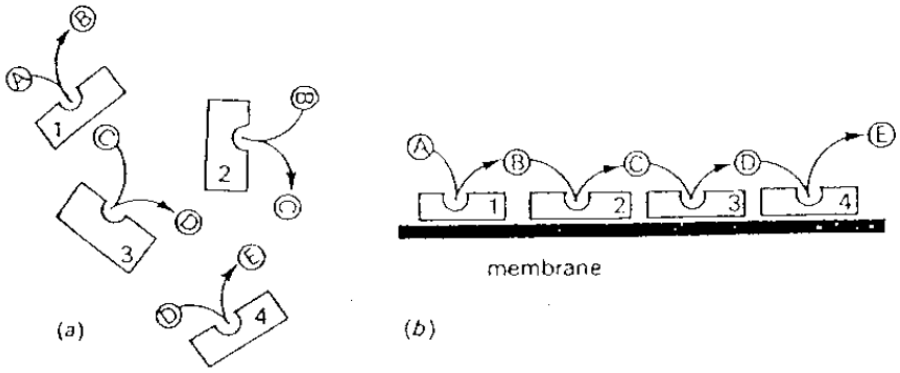
   - Plasma membrane contains glycoproteins and glycolipids, which serve as cell surface markers for cell-cell recognition. This allows cells to interact and adhere together.
   - This is crucial in the sorting of an animal embryo's cells into tissues, and is the basis for the rejection of foreign cells by the immune system.

4. **Cell communication / Signal transduction with:**

   - **external environment**: Plasma membrane contains certain glycoproteins which act as receptor sites for sensing external stimuli (e.g. hormones, growth factors and neurotransmitters), thus triggering specific responses within the cell.
   - **between organelles**: membrane proteins allow for communication between organelles.

5. **Site for formation of multi-enzyme complexes**

   - Many enzyme-catalysed reactions in cells are limited by the low concentrations (usually on the order of 10^{-6} M or lower) of both substrate and enzyme molecules in the cell. This limits the frequency with which enzymes collide with their substrates to form enzyme-substrate complexes.
   - To increase reaction rates without raising substrate concentrations, various enzymes involved in a reaction sequence (series of coordinated reactions known *as a **metabolic pathway**,* with each reaction catalysed by a specific enzyme) can be brought together on membranes to form a large protein assembly known as a **multi-enzyme complex**.



Multi-enzyme complexes.
(a) Enzymes 1-4 are free in solution. (b) Enzymes 1-4 are attached to a membrane in a sequential manner.

- For the metabolic pathway illustrated in the diagram above, conversion of A to end product E can be sped up significantly if the four enzymes involved are attached in a sequential manner on the membrane surface in (b). This allows the product of enzyme 1 to be passed directly to enzyme 2, and so on. Conversion of substance A to the end product E would be far less efficient if the enzymes and the various intermediate products diffused randomly in the cytosol as illustrated in (a).

6. **Compartmentalisation within the cell**

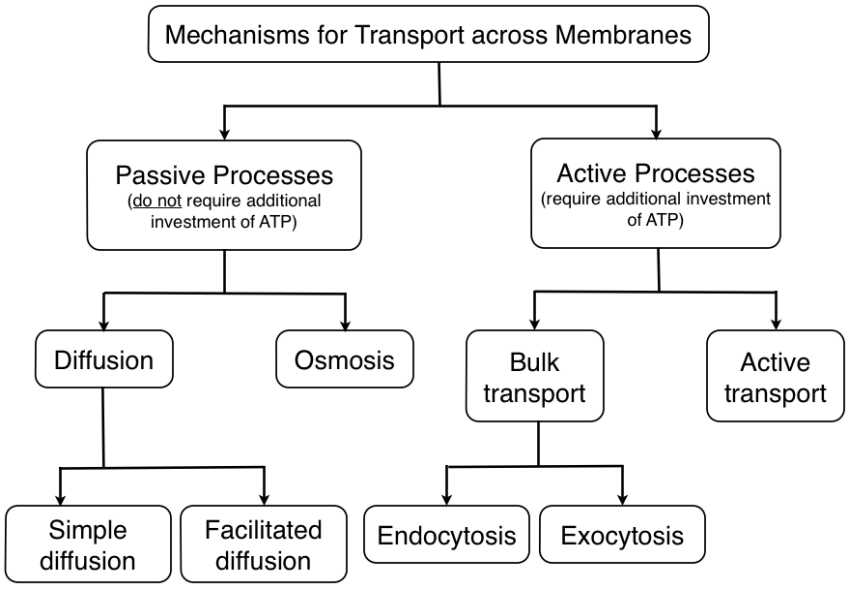
- Intracellular membranes compartmentalise the contents of eukaryotic cells into organelles, and even different compartments within the organelles.
  - Provides localised environmental conditions within the organelles that facilitate specific metabolic processes to proceed simultaneously. e.g. lysosomes enclose an acidic environment that allows their acid hydrolases to be active.
  - Enables cell to maintain high concentrations of certain enzymes and substrates in specific compartments. e.g. multi-enzyme complexes, this serves to significantly speed up metabolic reactions.
  - Prevents intermediates of one pathway from interfering with those of another. Therefore, this allows incompatible reactions to be carried out simultaneously in different organelles of the same cell.
  - Isolates harmful substances from the rest of the cell. e.g. lysosomes that contain hydrolytic enzymes.

III. Transport Across Membranes

The hydrophobic core of the cell membrane prevents the passage of most polar molecules and charged ions. This barrier allows the cell to maintain concentrations of solutes in its cytosol that differs from the extracellular environment, and intracellular membrane bound compartments. However, transport across membranes must still occur for various reasons:

- To allow cells to take up nutrients and oxygen
- To allow cells to excrete waste products
- To allow cells to secrete useful substances
- To generate ionic gradients which are essential for nervous and muscular activities
- To maintain suitable pH and ionic concentrations within various compartments of the cell for enzyme activity

The following diagram summarises the various mechanisms by which transport across membranes occurs:

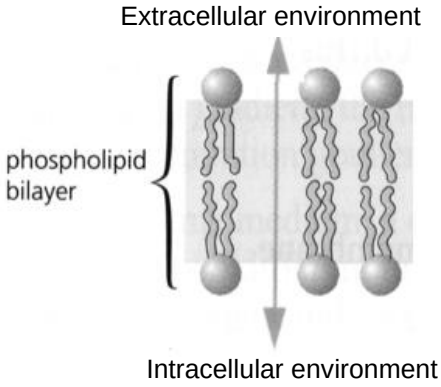


A. Passive Processes

1. Simple Diffusion

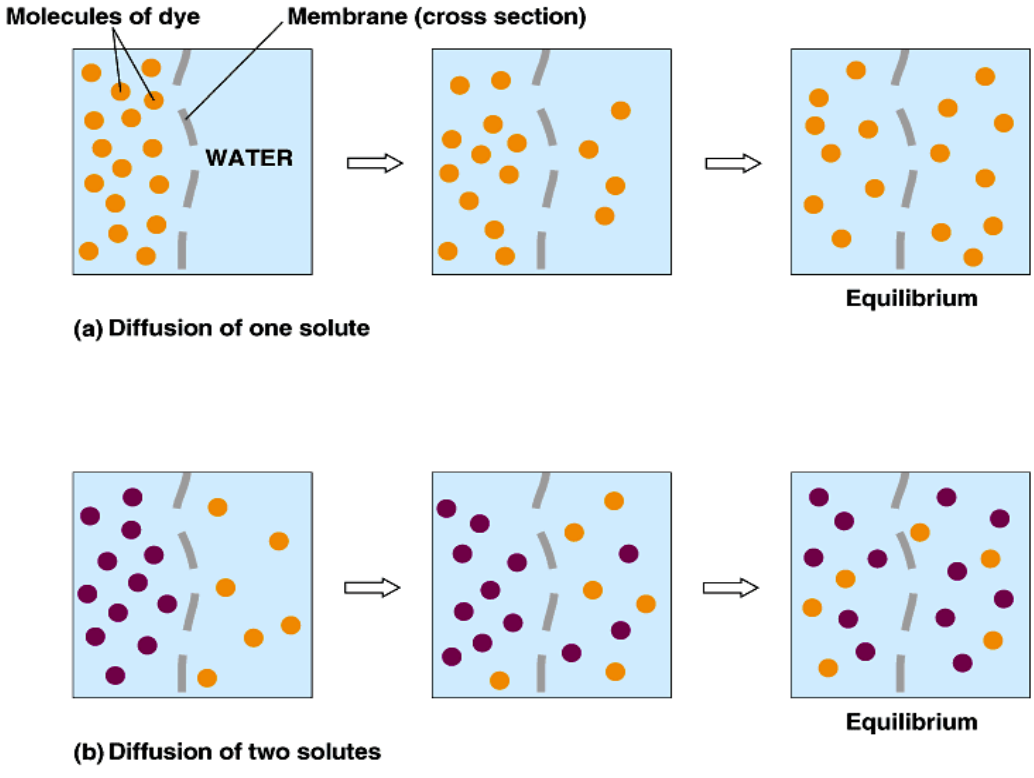
- **Definition of diffusion**: The net movement of a substance from a region of higher concentration to a region of lower concentration, i.e. down a concentration gradient.
- The process is passive as it does not require additional investment of energy by the cell in the form of ATP.
- It occurs spontaneously as the chemical potential energy stored in the particular concentration gradient translates into the kinetic energy of particles moving down the concentration gradient.

In **simple diffusion**, the particles can move in either direction across the lipid bilayer, through the intermolecular spaces ("**transient gaps**") among the membrane phospholipids.



Simple diffusion across phospholipid bilayer through transient gaps between adjacent phospholipid molecules. This occurs readily for small, non-polar and uncharged molecules like O_2 and CO_2

- Each type of particle moves down its own diffusion gradient independently of other molecules.
- Eventually, a state of dynamic equilibrium is reached when there is equal distribution of particles of the particular substance on both sides of the membrane, and there is no net movement of particles in any direction.



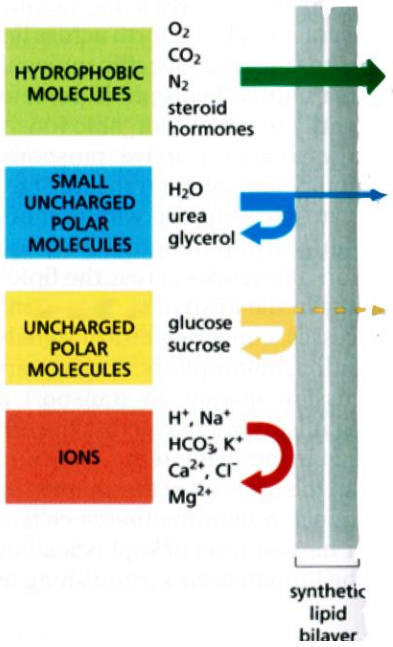
The diffusion of solutes across a membrane. Source: Biology, Pg 132.

Some substances can pass through membranes by simple diffusion

- Small, non-polar and uncharged molecules are able to interact with the hydrophobic core of membranes and thus can diffuse rapidly across membranes through transient gaps.

- Small, but polar molecules are small enough to slip through the transient gaps and pass through the hydrophobic region of the membrane, but at a very slow rate.
- Polar and uncharged molecules such as sugars and fatty acids move across the membrane at negligible rate.
- Large molecules and charged ions are unable to pass through the hydrophobic region of the membrane by simple diffusion.

∗ Other transport mechanisms are therefore necessary to facilitate the diffusion of polar and charged substances across membranes.



Source: Molecular Biology of the Cell, Pg 652.

Factors affecting rate of simple diffusion

1. Particle size
   - The smaller the particle size, the faster the rate of diffusion.
   - Smaller particles are more likely to be able to pass through the transient gaps among the membrane phospholipids.

2. Solubility in lipid bilayer
   - Non-polar and uncharged molecules (e.g. carbon dioxide, oxygen) are hydrophobic, and thus are able to penetrate the hydrophobic region of the membrane. Hence, they can readily pass through the lipid bilayer via simple diffusion.
   - Polar and uncharged molecules pass through much more slowly, especially if they are larger in size.
   - Membranes are highly impermeable to charged ions, no matter how small, because the charge and high degree of hydration of such molecules prevents them from entering the hydrocarbon region of the membrane.

3. Concentration gradient
   - The steeper the concentration gradient, the faster the rate of diffusion. This is a linear relationship.

4. Temperature
   - The higher the temperature, the greater the kinetic energy of the particles, and thus the higher the rate of diffusion.
   - Very high temperatures can disrupt the integrity of a membrane, causing it to lose its selectivity as a barrier.

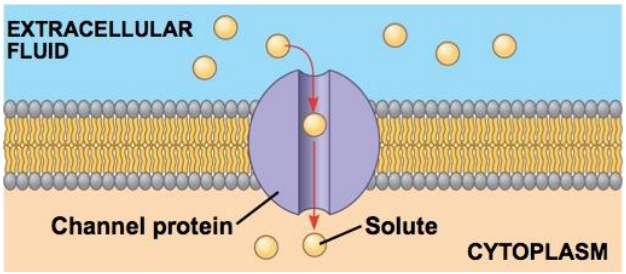
5. Surface area of membrane
   - The larger the surface area over which diffusion can occur, the greater the number of molecules that can diffuse through the membrane per unit time, thus the higher the rate of diffusion.
     - e.g. microvilli increase the surface area of animal cells for absorption purposes

6. Length of diffusion path
   - The shorter the distance over which diffusion occurs, the faster the diffusion process.
   - e.g. the thinner the membrane, the faster the diffusion.

2. Facilitated Diffusion

- **Definition of facilitated diffusion**: The net movement of a substance from a region of higher concentration to a region of lower concentration across a selectively permeable membrane with the help of transport proteins, without extra investment of energy in the form of ATP by the cell.
- There are two types of transport proteins involved in facilitated diffusion: **Channel proteins** and **Carrier proteins**.

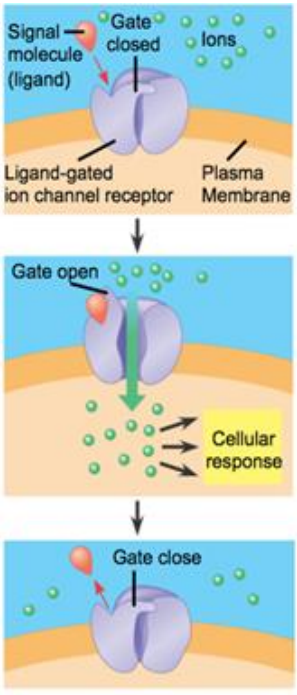
1. Channel proteins



Source: Biology, Pg 135

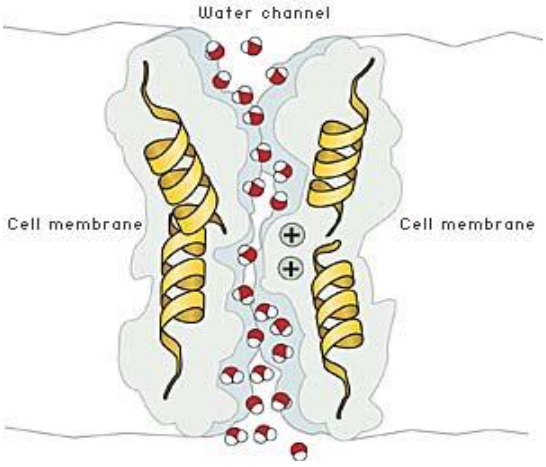
- These are transmembrane proteins with a fixed three-dimensional conformation. They form hydrophilic channels whose shape is specific for a particular polar molecule or charged ion.
- These channels allow specific hydrophilic solutes to cross the membrane without coming into direct contact with the hydrophobic interior of the membrane.
- Channel proteins include
  - i. **Gated channels** that open or close in response to a chemical, electrical or mechanical stimulus, depending on the type of channel:

    e.g. stimulation of a nerve cell by certain neurotransmitter molecules opens gated channels that allow the influx of sodium ions. *(KIV: Hormonal Control)*



Example of a gated ion channel that opens in response to a chemical stimulus

Source: Biology, Pg 213.



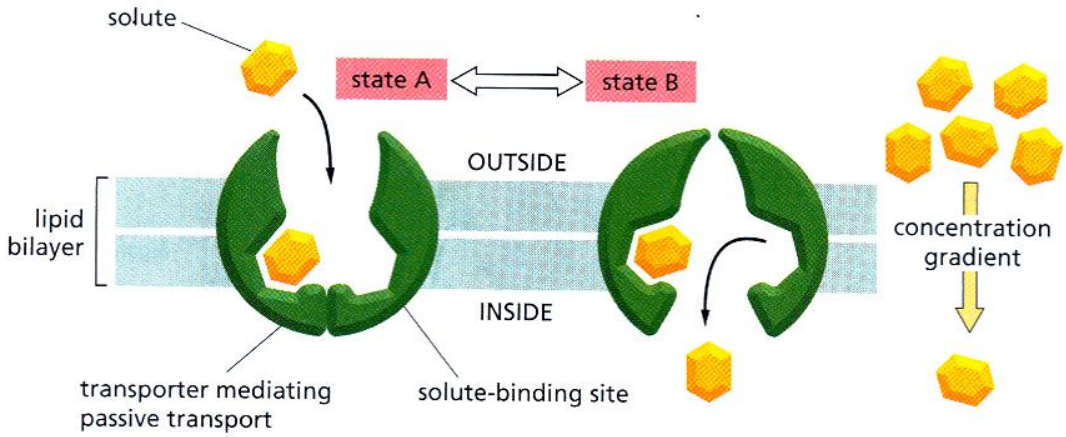
Diagrammatic representation of non-gated channel: aquaporin

  - ii. **Non-gated channels** that are continuously open:

    e.g. **aquaporins** (water channel proteins) that transport water molecules across membranes. Kidney cells have a high number of aquaporins, allowing them to reclaim water from urine before it is excreted.

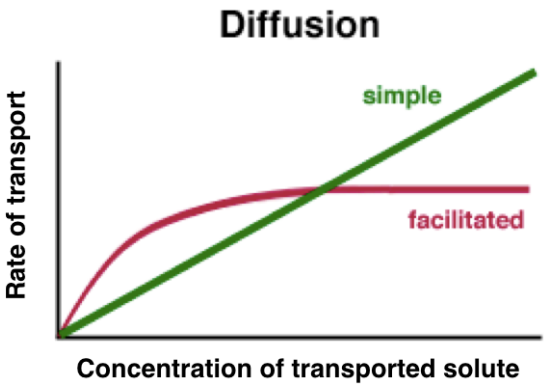
2. **Carrier proteins**

- These are transmembrane proteins that bind the specific solute to be transported and undergo a series of rapid conformational changes to transfer the bound solute across the membrane.
  - e.g. glucose carrier proteins are found in the membranes of most mammalian cells to bring glucose into cells for respiration.
- Carrier proteins exist in two conformational states. The binding site faces one side of the phospholipid bilayer in one state and the other side of the phospholipid bilayer in the other state.



Factors affecting the rate of facilitated diffusion

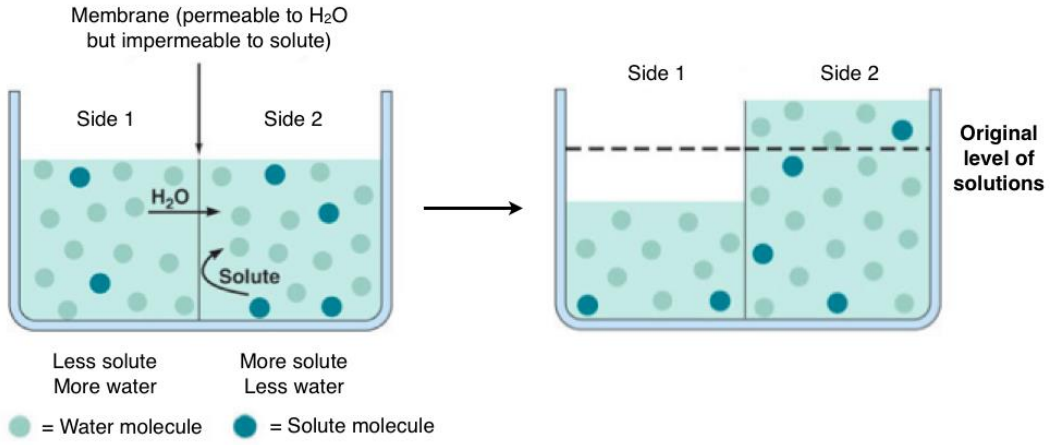
1. **Concentration gradient**
   - The higher the concentration of a solute, the higher the frequency of collisions between the transport protein and solute, and thus the higher rate of facilitated diffusion across the membrane.
   - However, when solute concentration reaches beyond a certain point, it is no longer limiting.
   - The number of transport proteins then becomes the limiting factor. Once the **transport proteins are saturated** (i.e. channel proteins are operating at their maximal rates, or binding sites of all carrier proteins are occupied), rate of transport reaches a maximum regardless of any further increase in solute concentration.



2. **Number of transport proteins for the specific solute**
   - The greater the number of transport proteins, the higher the rate of facilitated diffusion.

3. Osmosis

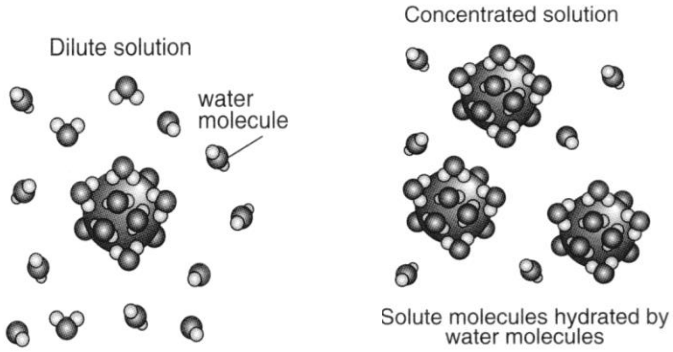
- **Definition of osmosis**: Net movement of water molecules from a region of less negative (higher) water potential to a region of more negative (lower) water potential across a selectively permeable membrane.



Water potential

Definition of Water potential (Ψ or Ψ_w): The measure of the tendency for water molecules to move from one place to another.

- Water potential is measured in terms of kilo Pascals (kPa).
- At standard temperature and pressure, pure water has the least negative (i.e. highest) water potential, which by definition is set as zero, i.e. Ψ_w of pure water = 0.



- The effect of dissolving solutes in pure water is to make water potential more negative, i.e. Ψ_w of a solution is always < 0.
    - This is because solute particles attract water molecules, forming a hydration shell. This restricts the movement of water molecules, thus making it less easy for them to leave the solution.
    - The more concentrated the solution, the more negative (i.e. the lower) the water potential becomes.
- Water moves down a water potential gradient, i.e. from a region of less negative (higher) water potential (e.g. -200 kPa) to a region of more negative (lower) water potential (e.g. -800 kPa).
    - When the two solutions achieve the same Ψ_w, they have reached dynamic equilibrium.

Components of water potential

- Two important factors affect water potential:
  - Presence of dissolved solutes (giving rise to a **solute potential**); and
  - Mechanical pressure acting on water (**pressure potential**)
- The relationship between these three terms is illustrated by this equation:

Water potential (Ψ)	=	**Solute potential (Ψ_s)**	+	**Pressure potential (Ψ_p)**
(usually negative, max 0)		*(always negative)*		*(usually positive or minimum 0)*

Solute potential

Definition of Solute potential (Ψ_s): The extent to which solute molecules lower Ψ. Ψ_s is always zero or negative in value.

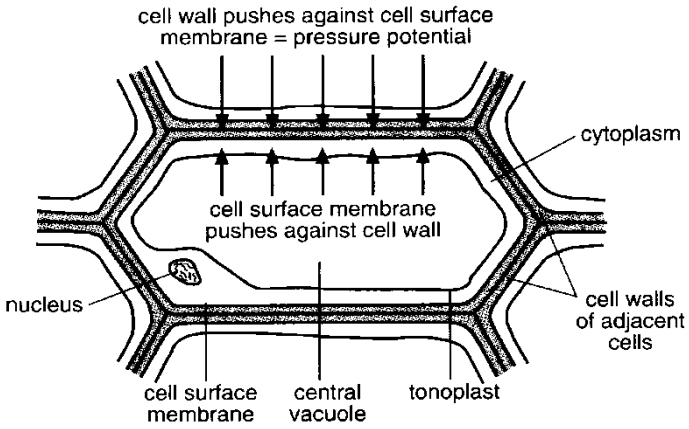
**Solute potential was also previously known as 'osmotic pressure' or 'osmotic potential'*

- The more solute particles, the fewer the number of free (unbound) water molecules, thus the more negative (lower) the solute potential.
  - e.g. the solute potential of 1M NaCl is more negative than that of 1M sucrose.

Pressure potential (only applicable to plant cells)

Definition of Pressure potential (Ψ_p): The extent to which external pressure acting on water increases Ψ. Ψ_p is usually positive or zero since it tends to move water out of cells, as opposed to solutes which tend to draw water into cells.

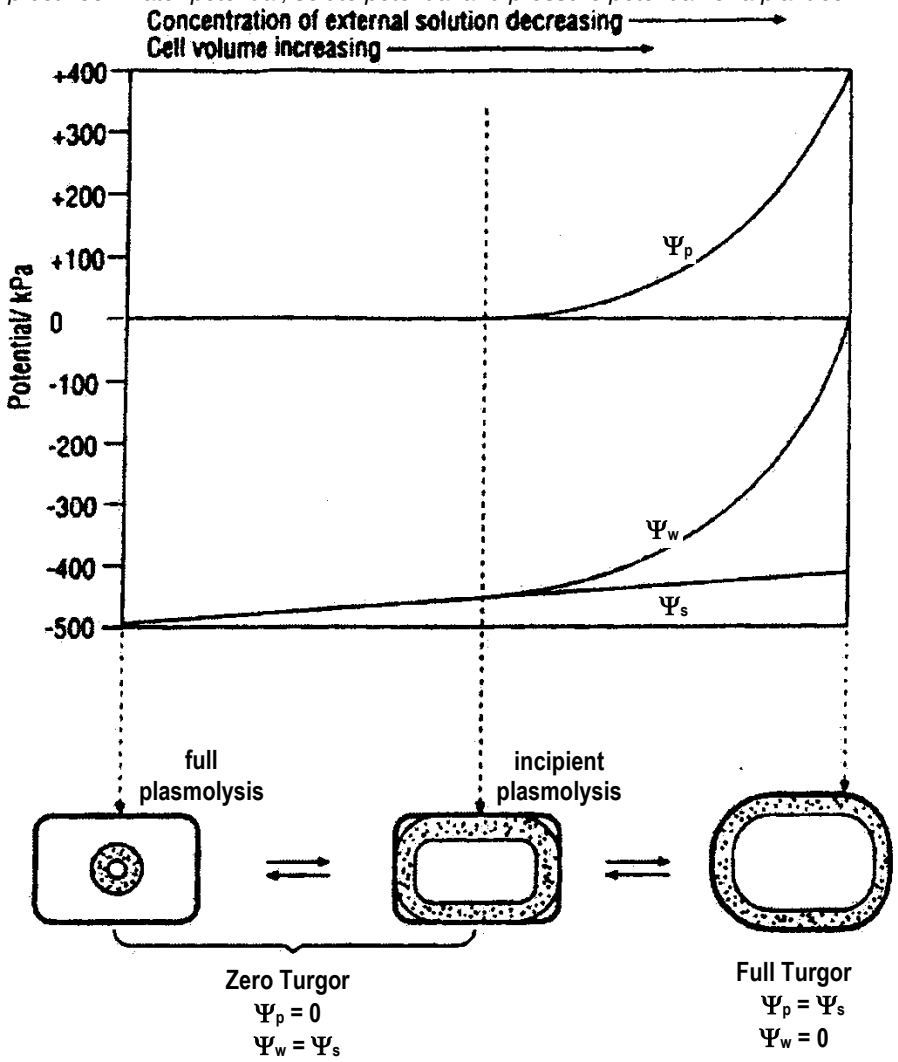
**Pressure potential was also previously known as 'turgor pressure' or 'wall pressure'.*



- If a pressure greater than atmospheric pressure is applied to water, it increases Ψ, thus making it less negative.
- This is the case in most plant cells. As water enters a plant cell, the contents of the cell start to push against the cell wall. In turn, the cell wall pushes back onto the expanding cell contents. This inward mechanical pressure is known as **pressure potential**.

Water potential in plant cells

Graph showing relationship between water potential, solute potential and pressure potential for a plant cell



- When a plant cell is placed in a solution that is more concentrated than its contents, it loses water by osmosis. Eventually, it reaches a point when the cytoplasm and plasma membrane withdraw from the cell wall – this is known as **plasmolysis**.
- **Incipient plasmolysis** is the point when the plasma membrane has just begun to shrink away from the cell wall.
    - At this point, Ψ_p **becomes 0** since the cell contents no longer exert pressure on the cell wall, and vice versa.
    - Therefore, $\Psi = \Psi_s$ from this point onwards.
- **Full plasmolysis** occurs when the cytoplasm shrinks to the extent that the cell membrane pulls completely away from the cell wall.
- If the **plasmolysed** cell is subsequently placed into pure water or a more dilute solution, water enters the cell by osmosis. This makes the cell contents more dilute, thus making solute potential (Ψ_s) less negative.
- Eventually, when sufficient water has been taken up to cause the cell contents to press against the cell wall, pressure potential (Ψ_p) is generated.
- With continuing water uptake, the cell continues to inflate and its wall is stretched. Ψ_p continues to rise until it reaches a value that completely offsets Ψ_s. At this point, water uptake ceases because Ψ has reached zero, i.e. its maximum value.

B. Active Processes

1. Active Transport

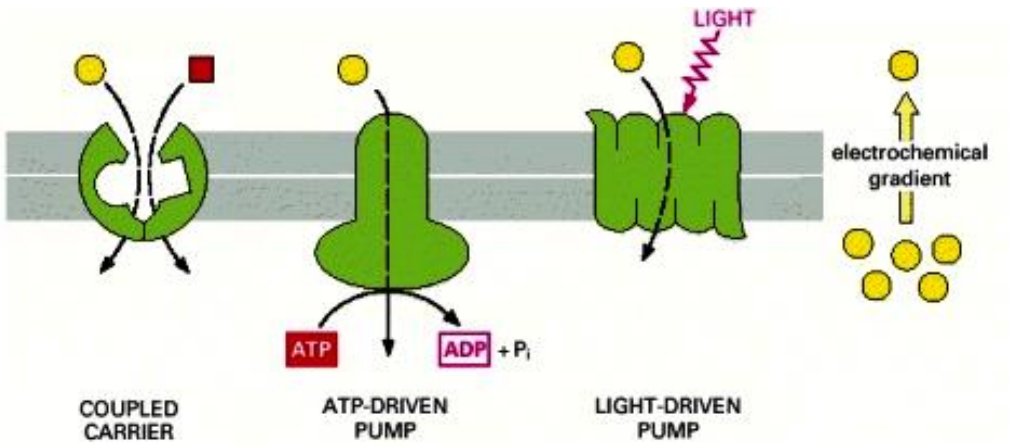
- **Definition of active transport**: The movement of particles from a region of lower concentration to a region of higher concentration, i.e. against a concentration gradient, across a selectively permeable membrane, with the additional investment of energy in the form of ATP.
- Active transport is energy-consuming since it drives the movement of substances against their natural tendency to diffuse in the opposite direction.

The Importance of Active Transport

- Active transport is important because it allows cells to:
  - Maintain internal concentrations of solutes that differ from concentrations in their environment
  - Take up nutrients even when concentrations outside cells are lower than those inside.
  - Remove waste products even when concentrations outside cells are higher than those inside
  - Maintain a voltage difference between the interior and exterior of the cell (i.e. membrane potential) due to different ion concentrations on either side of the cell membrane

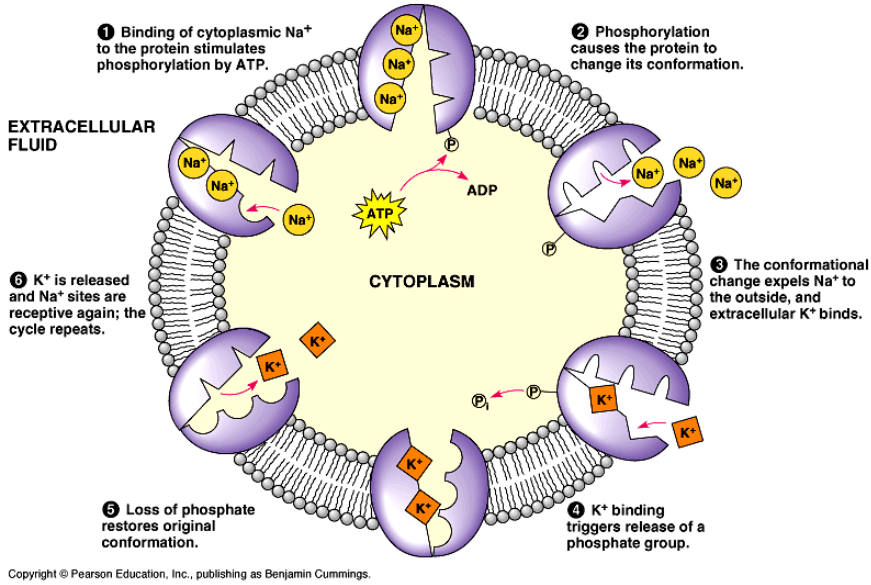
How Active Transport is Carried Out

- Active transport involves **carrier proteins** (*not channel proteins*) that pick up specific solutes and transport them against their concentration gradient.
- These carrier proteins must be linked to a source of energy to pump a solute uphill against its concentration gradient.
- Three main ways in which cells carry out active transport are:



Three ways of driving active transport

1. **ATP-driven pumps** couple uphill transport to the hydrolysis of ATP.
   - **sodium-potassium pump** in most cell membranes – actively removes three sodium ions from cells while actively pumping two potassium ions into the cell. ATP powers the shape change by phosphorylating the transport protein (i.e. by transferring a phosphate group to the protein)
   - Cells and tissues that carried out active transport are characterised by:
     - the presence of numerous mitochondria
     - a high concentration of ATP
     - a high respiratory rate

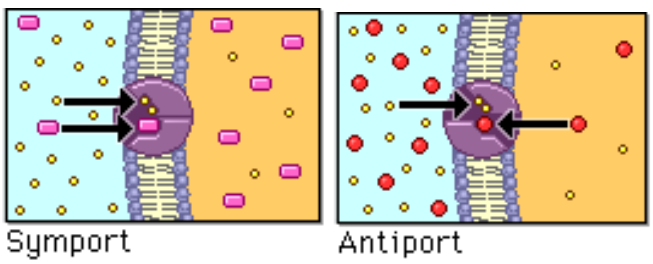


The sodium-potassium pump: a specific case of active transport. This transport system pumps ions against steep concentration gradients. The pump oscillates between two conformational states in a pumping cycle that translocates three Na^+ ions out of the cell for every two K^+ ions pumped into the cell. ATP powers the changes in conformation by phosphorylating the transport protein.

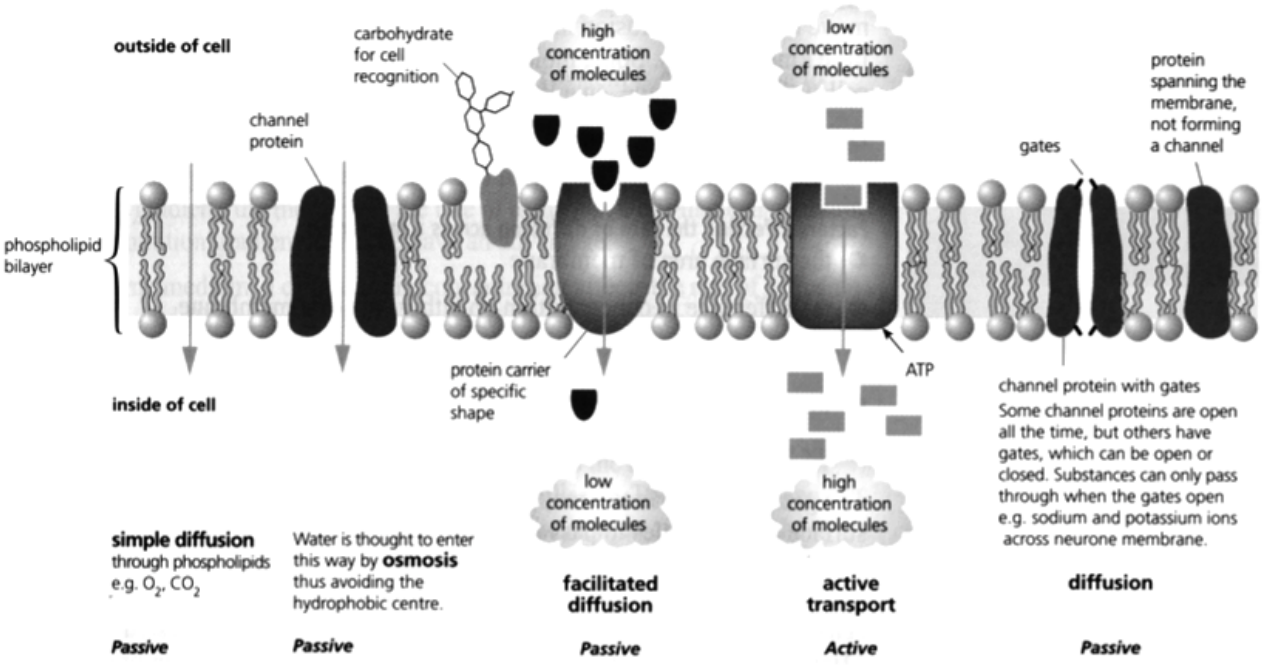
2. **Light-driven pumps**, which are found mainly in bacteria and archaea, couple uphill transport to an input of energy from light.
   - e.g. Photosynthesis in some bacteria involves transport of H^+ or Cl^- ions across a membrane. This transport is coupled to input of light energy.

3. **Coupled carriers** couple the uphill transport (*i.e. against concentration gradient*) of one solute across the membrane to the downhill transport (*i.e. down concentration gradient*) of another solute.

   In coupled carriers, the transport of one solute strictly depends on the transport of a second solute. This involves the simultaneous transfer of the second solute in the same direction across the cell membrane, as in **symport**; or the transfer of the second solute in the opposite direction across the cell membrane, as in **antiport**.



Summary of simple diffusion, facilitated diffusion and active transport across a membrane



Source: AS Level Biology, Pg 43.

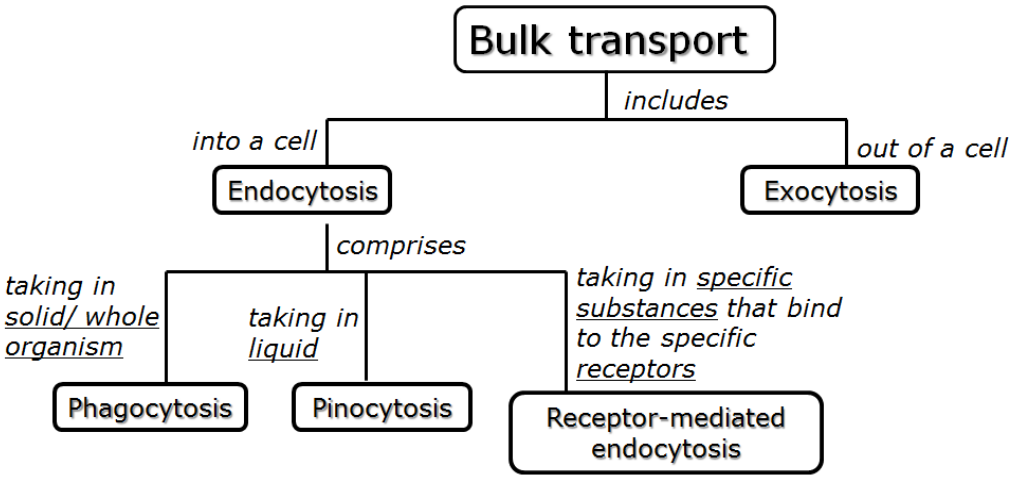
2. Bulk Transport

- **Definition of bulk transport**: The movement of relatively large quantities of macromolecules in and out of a cell.
- Bulk transport involves the process of **cytosis**.
- In cytosis, large molecules like proteins and polysaccharides are packed into vesicles (or vacuoles) and transported in or out of the cell, across the cell surface membrane.
- This process of cytosis:
  - is usually non-specific (except: receptor-mediated endocytosis)
  - requires energy in the form of ATP
  - involves breaking and reforming the phospholipid bilayer of the cell surface membrane

Advantages of cytosis

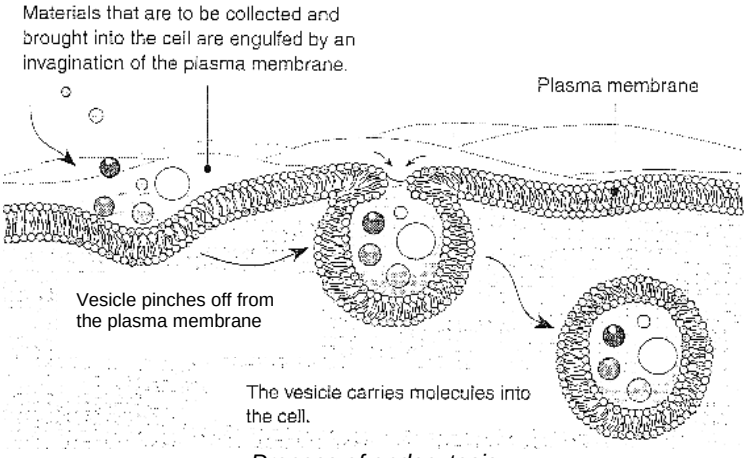
- Cytosis avoids the need for substances to move through the phospholipid bilayer of the cell membrane.
  - Substances move across the cell surface membrane due to pinching off or fusing of a small portion of phospholipid molecules in the phospholipid bilayer.
  - This process is made possible due to the fluidity of the cell surface membrane.
- Cytosis also provides a mechanism for rejuvenation or remodelling of cell membrane.
  - Cytosis occurs continually in most eukaryotic cells, yet the amount of plasma membrane remains fairly constant. Apparently, the loss of membrane due to endocytosis is offset by the gain of membrane in another exocytosis.

Cytosis can occur in two directions: into a cell (**endocytosis**) or out of a cell (**exocytosis**).



Endocytosis

- Endocytosis involves taking large molecules *into* a cell.
- A small portion of cell surface membrane **invaginates** to **enclose** the substances outside the cell. As the pocket deepens, it **pinches off** to form a **vesicle** containing the substances. The vesicle then gains entry into the cell as the cell surface membrane **reforms**.



Process of endocytosis

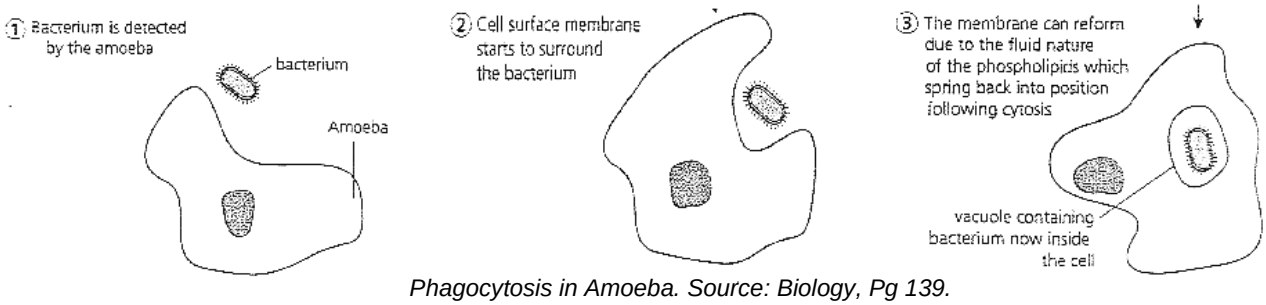
- There are three types of endocytosis:
  1. **Phagocytosis** ("cellular eating")
  2. **Pinocytosis** ("cellular drinking")
  3. **Receptor-mediated endocytosis**

1. Phagocytosis

- In phagocytosis, solid substances or even whole organisms are taken into a cell by invagination of the cell surface membrane.
- Sequence of events:
  1. A small portion of the cell surface membrane invaginates (or extending the **pseudopodia**[1], singular: pseudopodium) to enclose the solid particle.
  2. The particle is packaged within a membrane-enclosed sac that can be large enough to be called vacuole.
  3. Phagocytic vacuole pinches off from the cell surface membrane.
  4. Cell surface membrane reforms.

[1] Extension of pseudopodia is due to the evagination of the cell surface membrane.

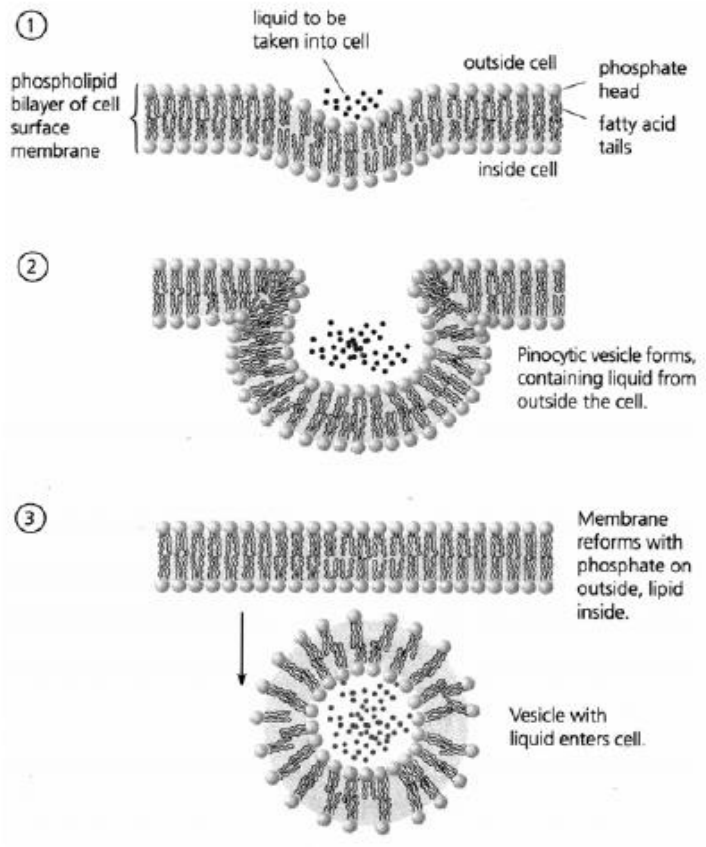
- Usually, the particles are digested after the vacuole fuses with a lysosome containing hydrolytic enzymes.
- Cells specialising in this process are called the **phagocytes** and are said to be phagocytic. The sac formed during this uptake is called a **phagocytic vacuole**.
- Examples of phagocytosis:
  - Unicellular organisms such as *Amoeba* taking in food particles
  - Phagocytic white blood cells engulfing certain types of bacteria



Phagocytosis in Amoeba. Source: Biology, Pg 139.

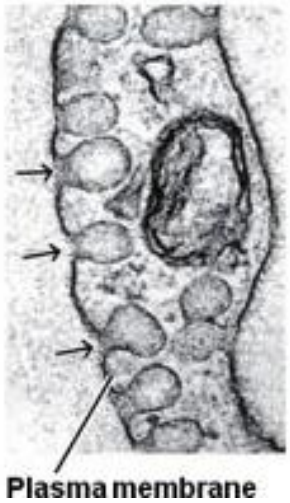
2. Pinocytosis

- Pinocytosis is similar to phagocytosis, except that the substances taken into the cell are in <u>liquid</u> form and soluble materials (solute).
- In pinocytosis, the cell takes in the extracellular fluid in tiny vesicles. The sac-like structure formed is often small, and is termed **pinocytotic vesicle**.
- It is not the fluid itself that is needed by the cell, but the molecule dissolved in the droplets.



Membrane structure during pinocytosis. Source: AS Level Biology, Pg 94.

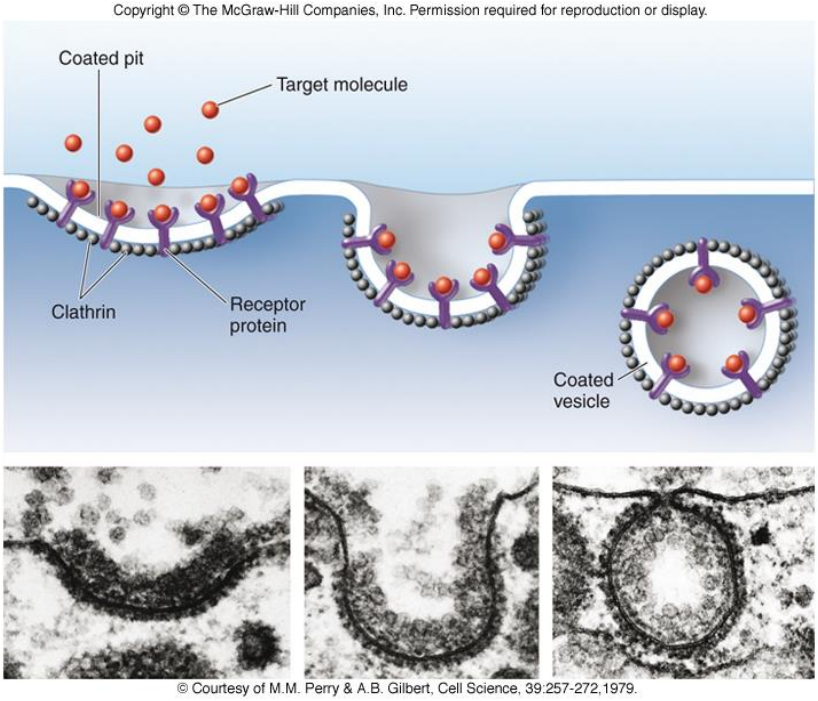
- Examples of pinocytosis:
  - Human egg cells taking in nutrients from surrounding follicle cells
  - In thyroid gland, follicle cells taking in thyroglobulin for conversion into thyroxine



Pinocytosis vesicles forming (arrows) in a cell lining a small blood vessel (TEM). Source: Biology (9th Ed), Pg 185.

3. Receptor-mediated endocytosis

- In receptor-mediated endocytosis, specific substances are taken into the cell, even though the substances are of low concentration in the extracellular fluid.
- This specificity is made possible by the receptor proteins embedded in the cell surface membrane. These proteins have specific receptor sites that are exposed to the extracellular fluid.
- The receptor proteins are found in regions of the cell membrane called coated pits. Coated pits have a fuzzy layer of **coat proteins** (e.g. clathrin) on their cytoplasmic side and receptors on the extracellular side.
- Sequence of events:
  1. When the specific substances, also known as **ligands** bind to receptor sites of receptor proteins, they trigger the invagination of the cell surface membrane.
  2. This results in the formation of **coated vesicles** that contain specific ligand molecules.
  3. After the ligands are taken up by the cell, the receptors are brought back to the cell surface membrane by the same vesicle.

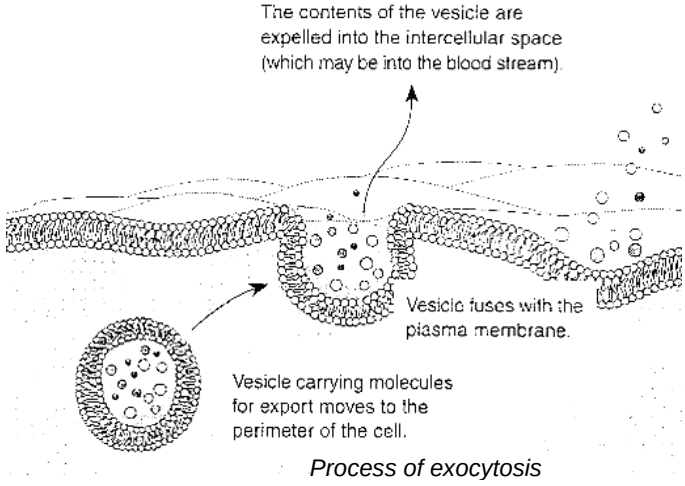


Source: Biology (9th Ed), Pg 185.

- Examples of receptor-mediated endocytosis:
  - Influenza virus has an outer envelope containing viral glycoproteins. These glycoproteins bind to specific receptors on the host cell membrane, allowing for the virus to enter and infect the host cell.
  - Human cells take in cholesterol (found in LDL) from blood via LDL receptors found on cell membrane. Individuals with defective LDL receptors have high level of cholesterol in blood and suffer from hypercholesterolemia.

Exocytosis

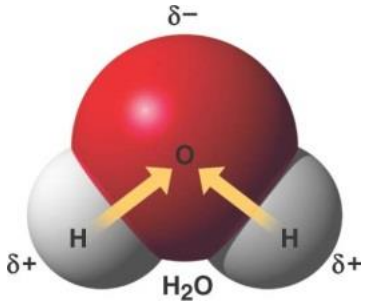
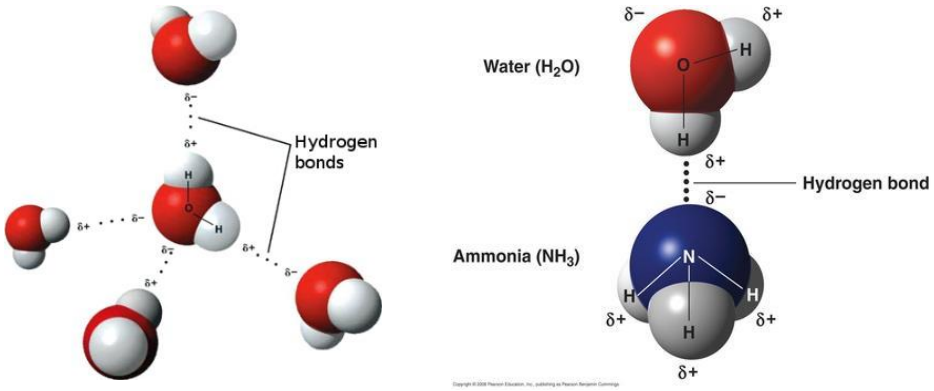
- In exocytosis, cell exports macromolecules through <u>fusion of membrane of vesicles</u> with the cell surface membrane.
- Sequence of events:
  1. Vesicles containing solids or liquids are first isolated in the cell from the cell by an internal membrane (i.e. membrane from Golgi apparatus).
  2. Vesicle <u>moves towards</u> the cell surface membrane and membrane of vesicle <u>fuses</u> with a small portion of the membrane, enabling the contents of the vesicles to be <u>released</u> from the cell via exocytosis.
  3. Cell surface membrane then reforms.

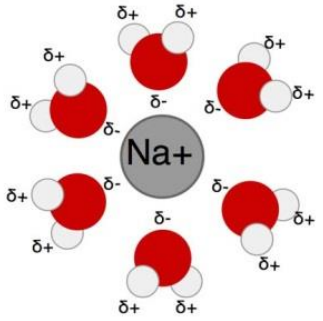
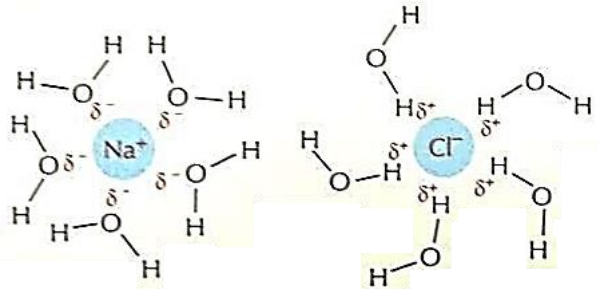


Process of exocytosis

- Examples of exocytosis:
  - Proteins and carbohydrates from Golgi vesicles are transported to the outside of the plant cell for making of cell wall.
  - Secretion of extracellular enzymes, hormones, antibodies and removal of waste products of lysosomal digestion.
  - Nerve cells (neurons) secreting neurotransmitters to signal other neurons or muscle cells.

ANNEX

Glossary	
polar molecule	A molecule (such as water) with an uneven distribution of charges in different regions of the molecule. This is due to difference in electronegativities between 2 atoms. e.g. oxygen is more electronegative than hydrogen, shared electrons are pulled more toward oxygen. This results in a partial negative charge on the oxygen and a partial positive charge on the hydrogens. In living cells, the common electronegative elements are usually oxygen or nitrogen atoms. 
ion	An atom or group of atoms that has gained or lost one or more electrons, thus <u>acquiring a charge</u>. e.g. chloride atom gained an extra electron giving it a net electrical charge of 1-, it has become a chloride ion (Cl^-). e.g. in the salt ammonium chloride, the anion is a single chloride ion (Cl^-) but the cation is ammonium (NH_4^+).
hydrogen bond	A type of weak chemical bond that is formed between polar molecules. e.g. when the partial positive charge on a hydrogen atom that is covalently bonded to an electronegative atom allows the hydrogen to be attracted to a different electronegative atom nearby. 

hydration shell	A sphere of water molecules around a dissolved ion. 
hydrophilic	Substances that have an affinity for water. They are composed of ions or polar molecules that attract water molecules through electrical charge effect.  
hydrophobic	Substances that have no affinity for water. e.g. hydrocarbons which contain many C-H bonds, water molecules are not attracted to such molecules.